Istituto Nazionale di Astrofisica

Osservatorio Astronomico di Brera

The optical counterparts of Accreting Millisecond X-ray Pulsars in quiescence: an observational review

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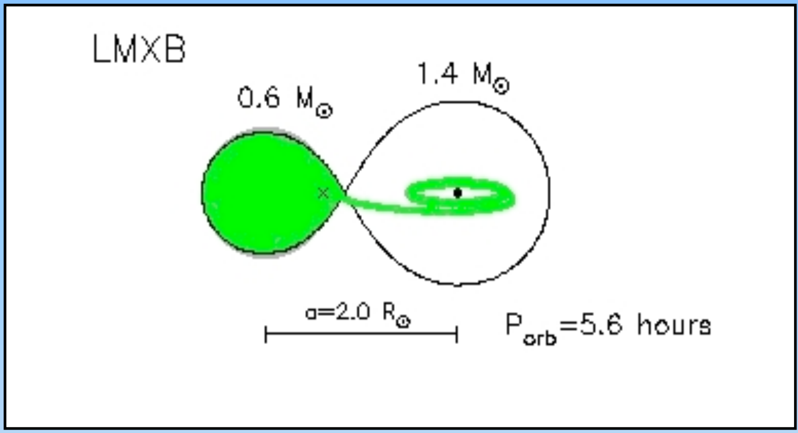
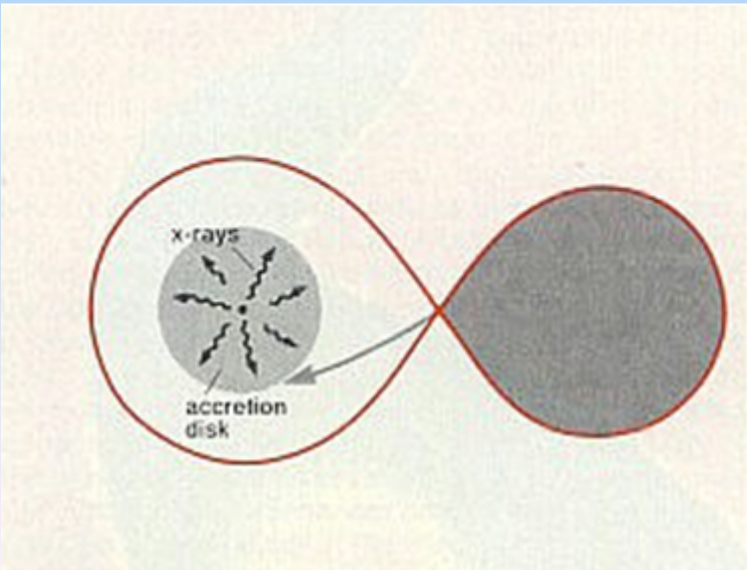
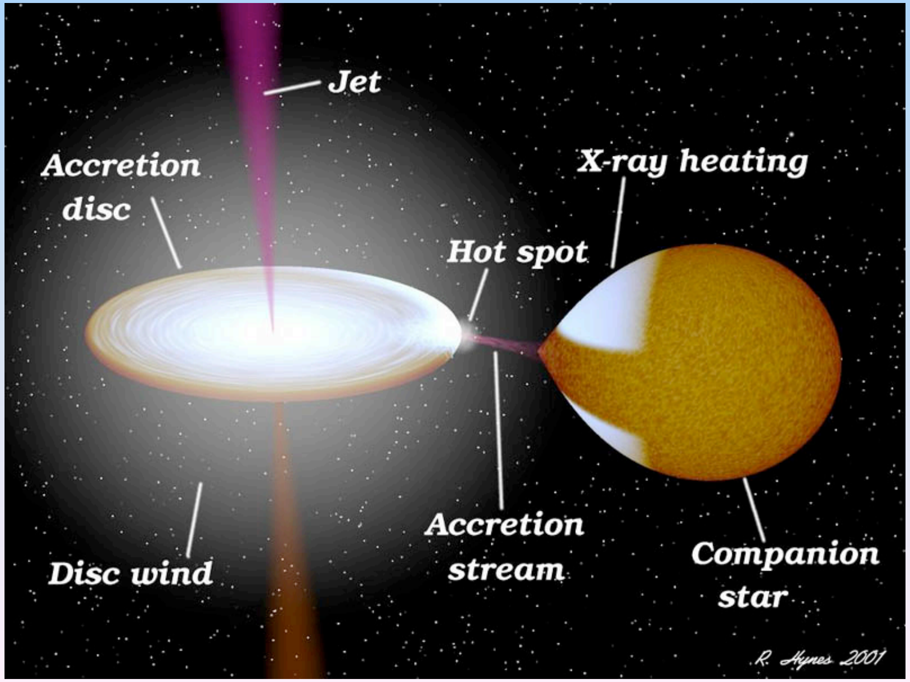
Low Mass X-ray Binaries

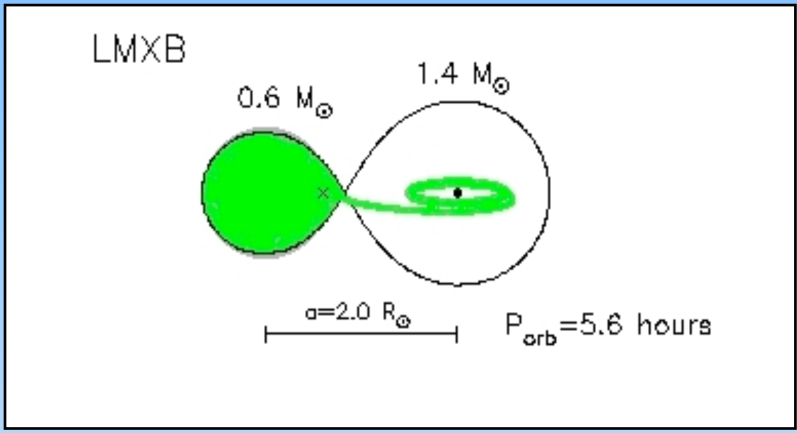


- Binary systems
- Low mass companions
- Roche lobe overflow





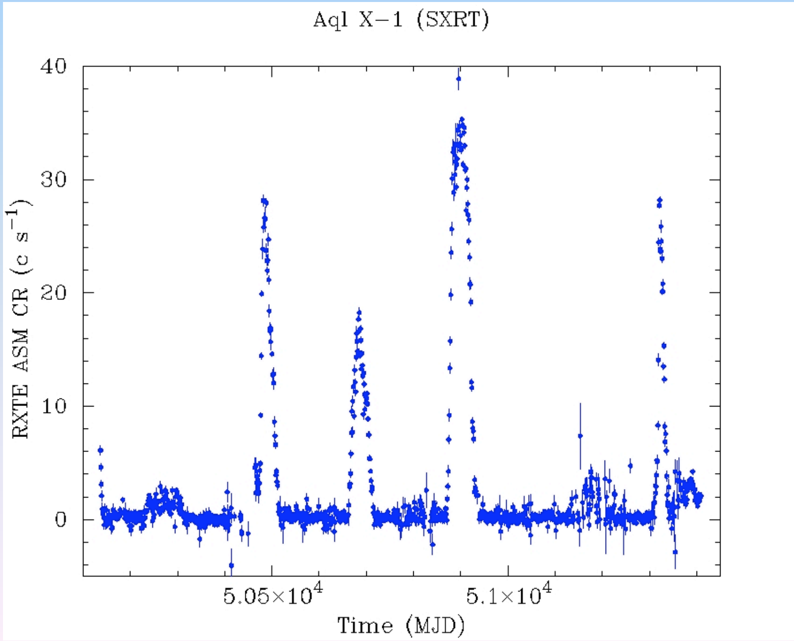
Low Mass X-ray Binaries
&
Low Mass X-ray Transients



- Binary systems
- Low mass companions
- Roche lobe overflow

LMXTs

- sporadic outbursts
- long quiescent periods



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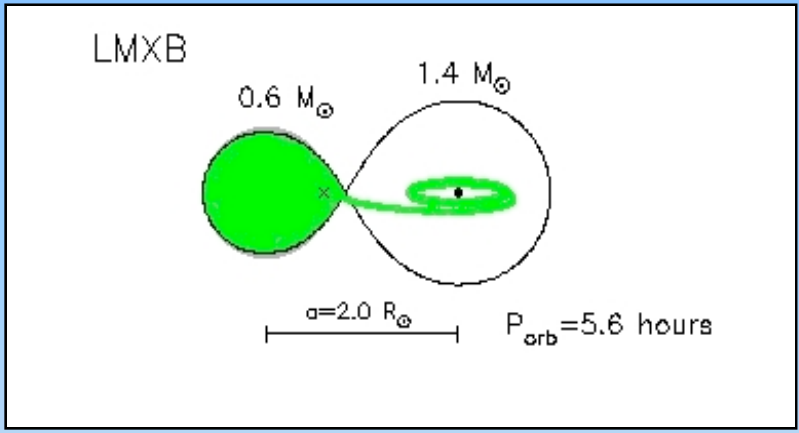
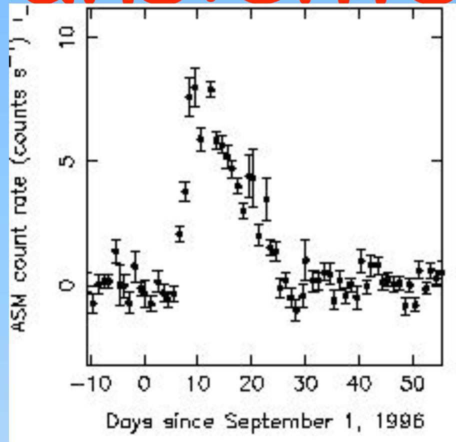
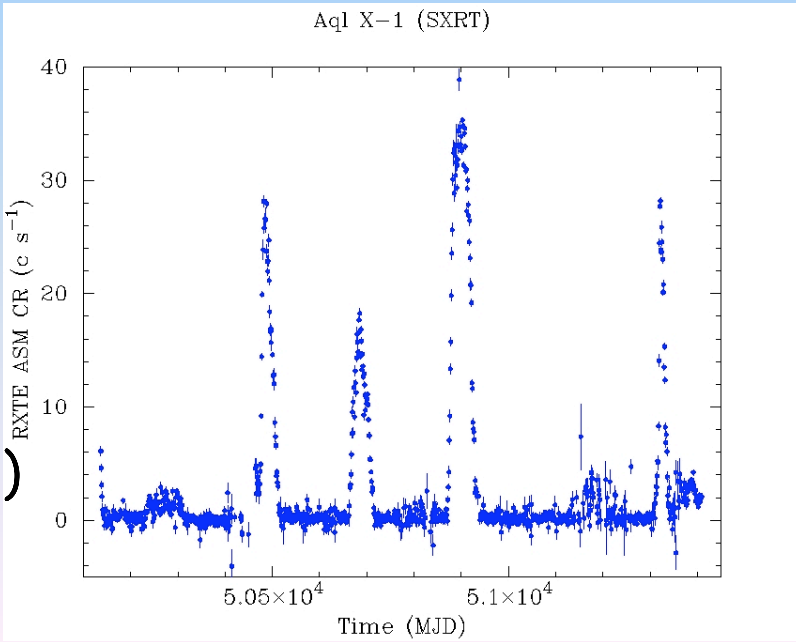




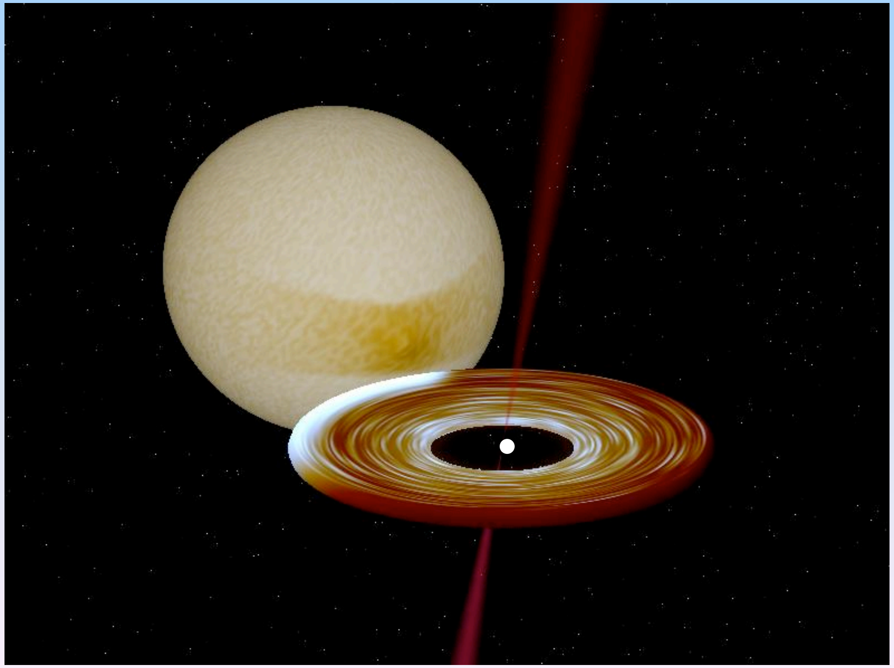


LMXTs

- sporadic outbursts
  - weeks to months duration
- long quiescent periods:
  - faint X-ray lum (10^{32}-10^{33} erg/s)
  - 6 – 7 mag fainter in optical with respect to outburst
  - little or no accretion

The study of LMXTs during quiescence

- Unique opportunity to detect the companion
- Origin of the quiescent optical emission:
  companion, disk, irradiation...



BinSim R. Hynes

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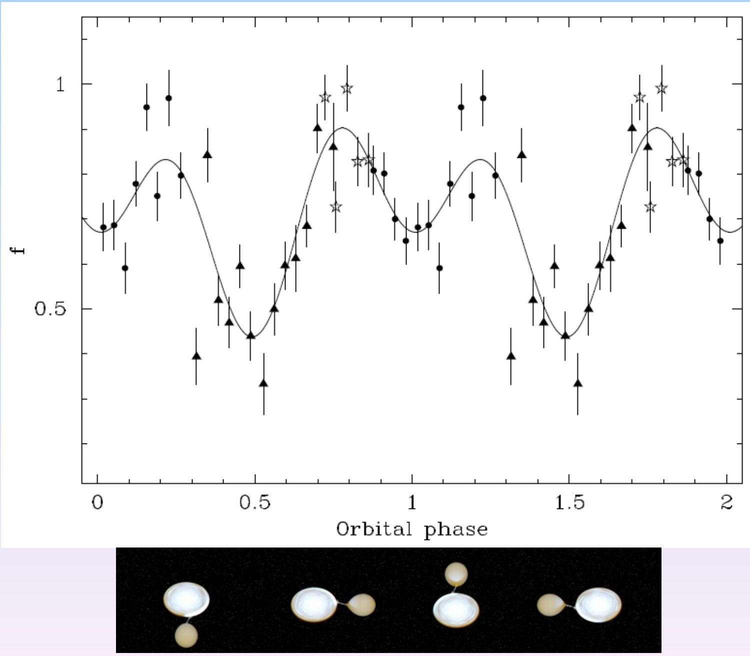
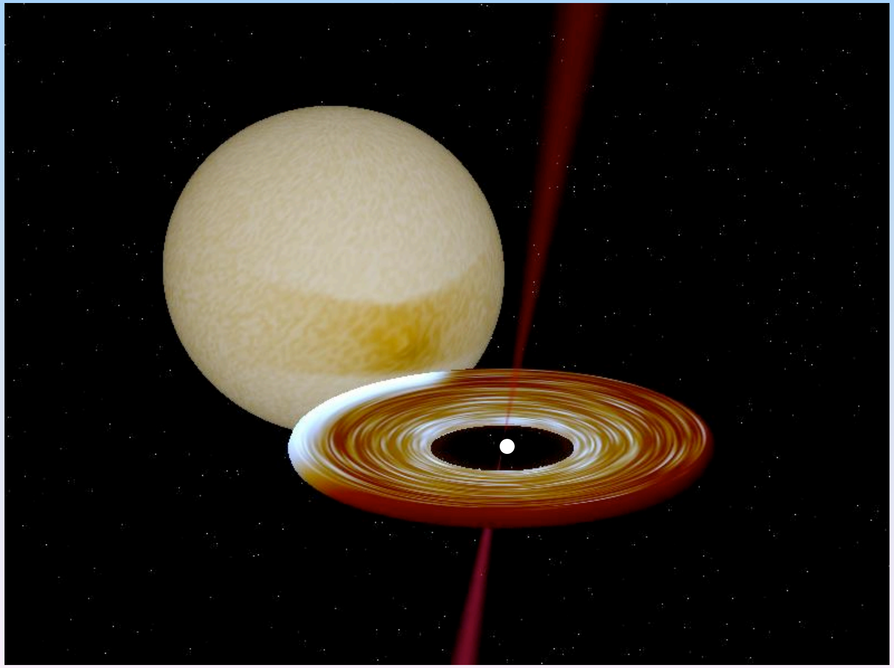


phase 0 phase 0.25 phase 0.5 phase 0.75



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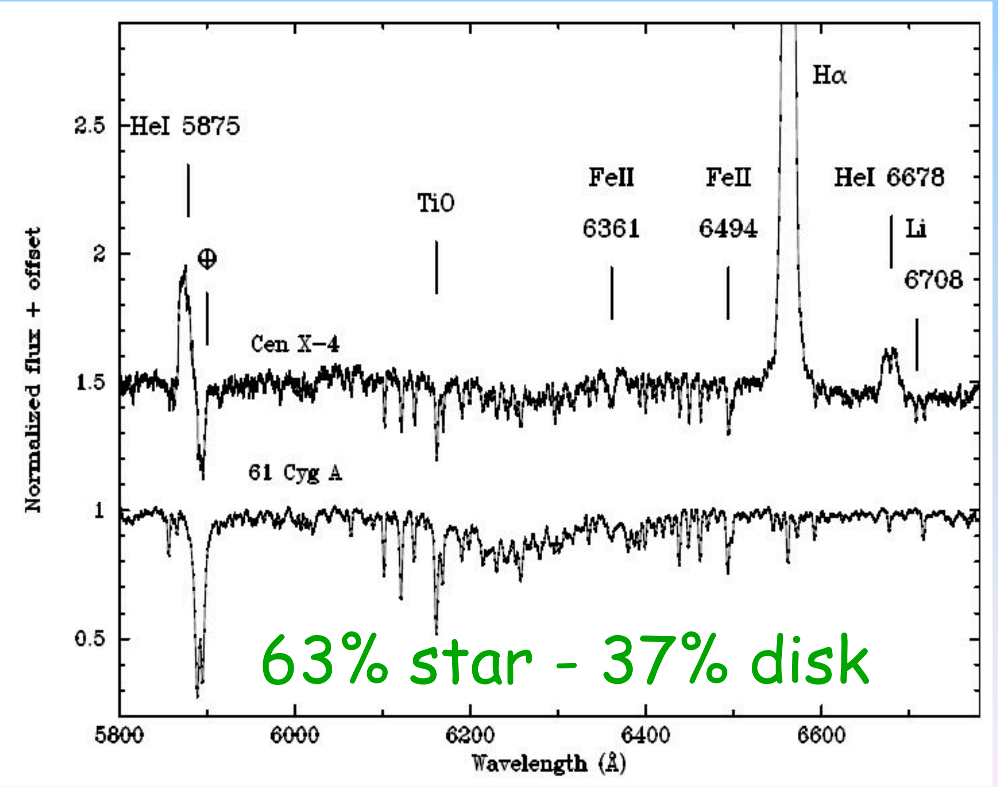
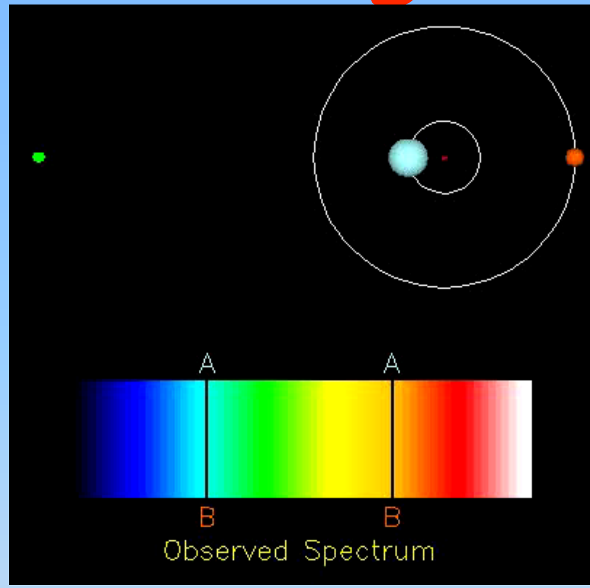


D'Avanzo et al. 2005

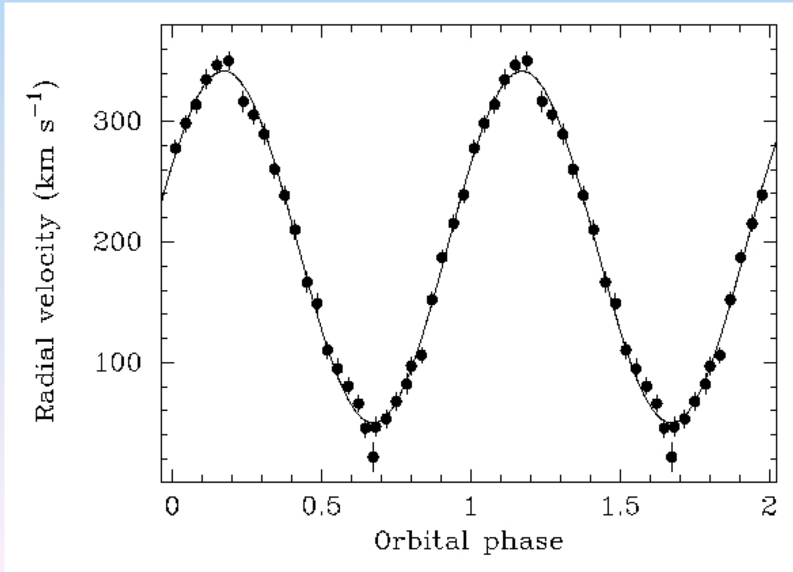
The study of LMXTs during quiescence



- Unique opportunity to detect the companion
- Radial velocity curve of the companion
- Optical mass function

$$\begin{cases} f_c(M) \equiv \dfrac{P_{orb} {K_c}^3}{2\pi G} = \dfrac{M_X sin^3 i}{(1+q)^2} \\ f_X(M) \equiv \dfrac{4\pi^2 (a_X sin\, i)^3}{G {P_{orb}}^2} = \dfrac{M_c sin^3 i}{(1+1/q)^2} \end{cases}$$

$$M_X = \frac{(1+q)^2}{sin^3 i} f_c(M)$$

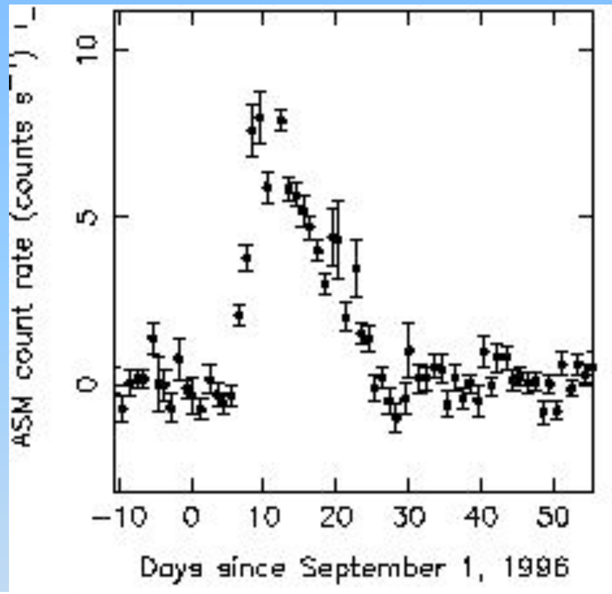


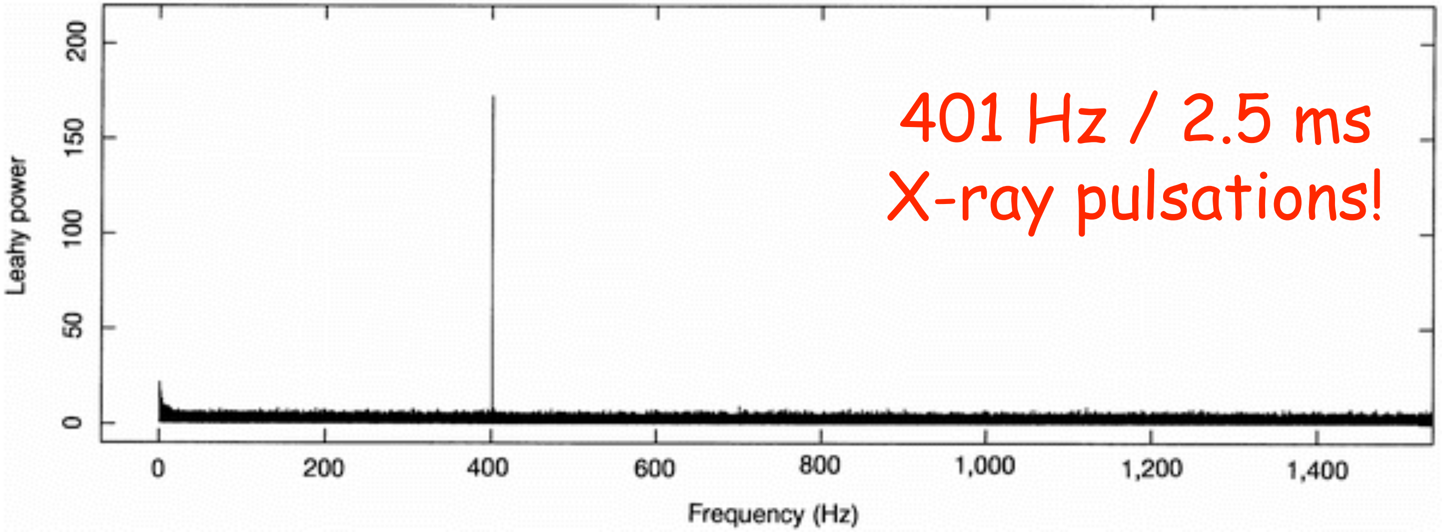
Accreting Millisecond X-ray Pulsars (AMXPs)

- 1998: the revolution

SAX J1808.4-3658

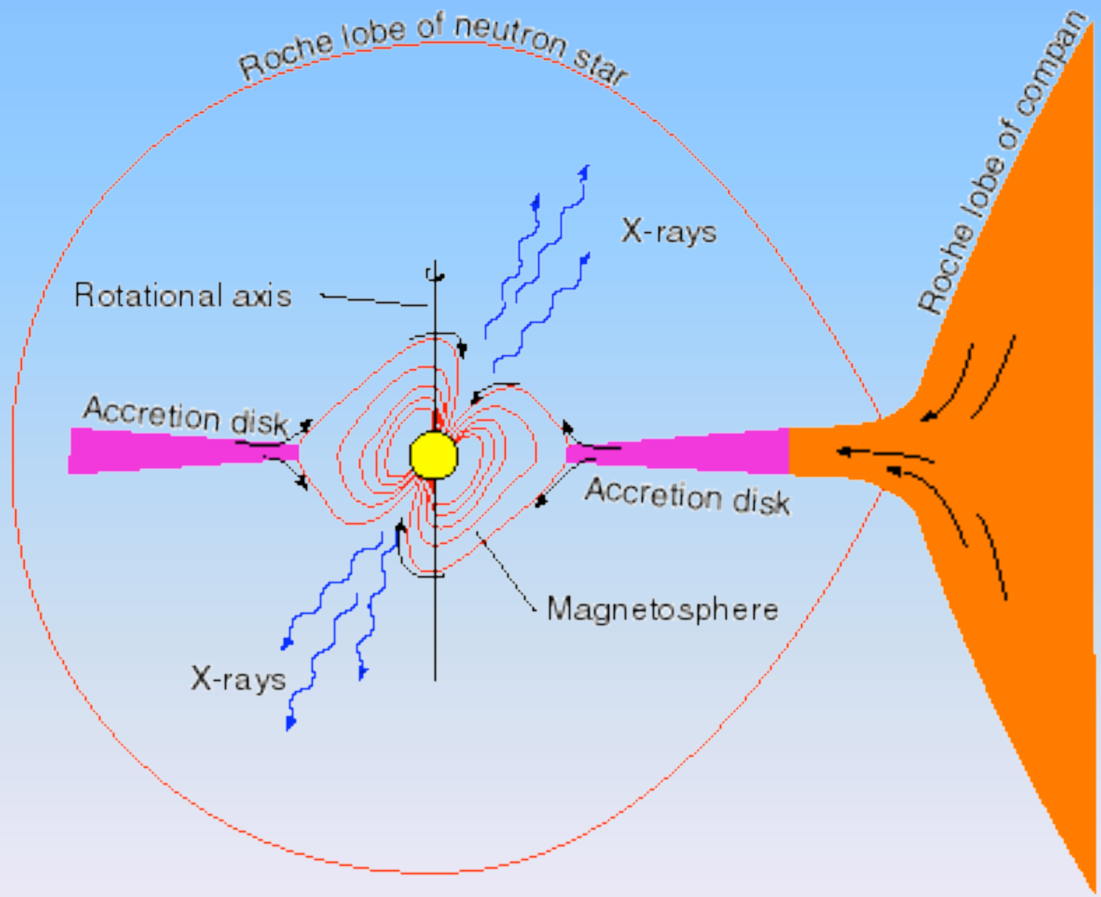
(in't Zand et al. 1998)





Wijnands & van der Klis (1998)
Nature

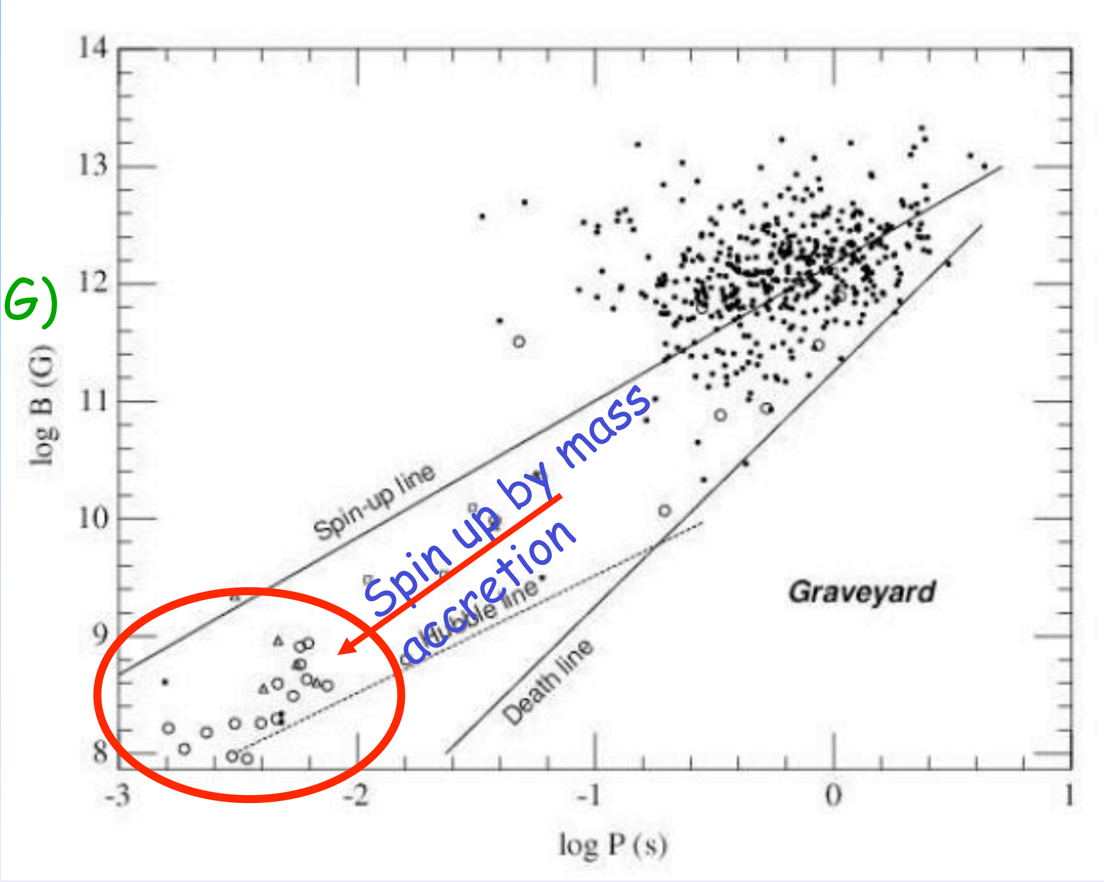
SAX J1808.4-3658: a ms X-ray pulsar



MSPs: recycling model

(Alpar et al. 1982; Bhattacharya & van den Heuvel 1991)

- rapid spin (ms)
- low magnetic field (B ~ 10^8-10^9 G)
- spin-up process
- progenitors: accreting LMXBs



All AMXPs were found in LMXBs transient systems: rapidly spinning NS
AMXPs can be the missing link between LMXBs and MSPs!

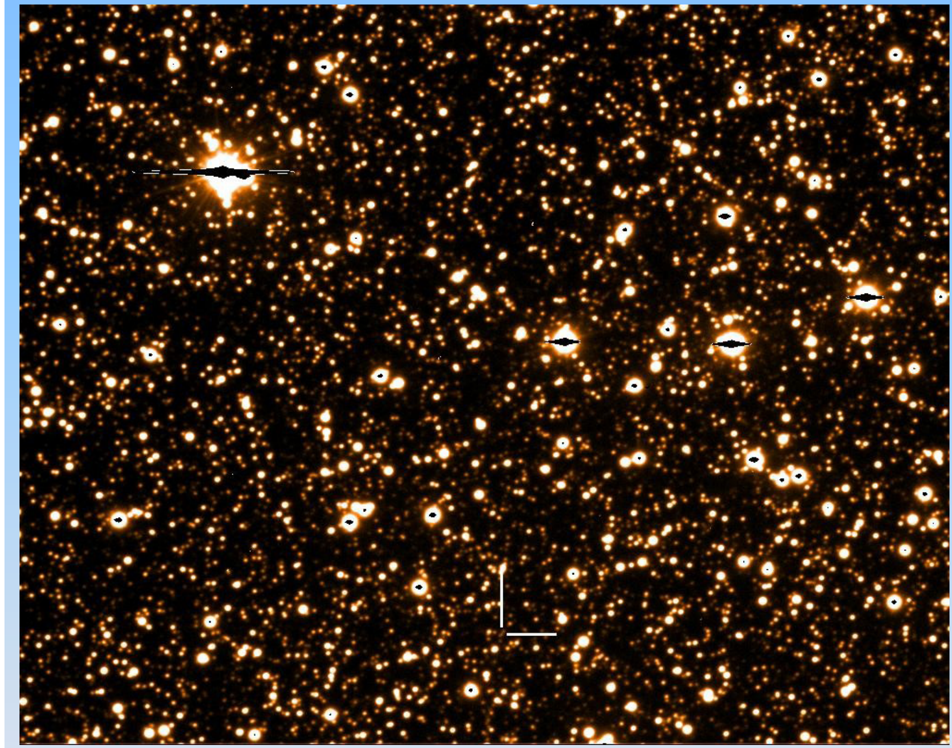
AMXPs

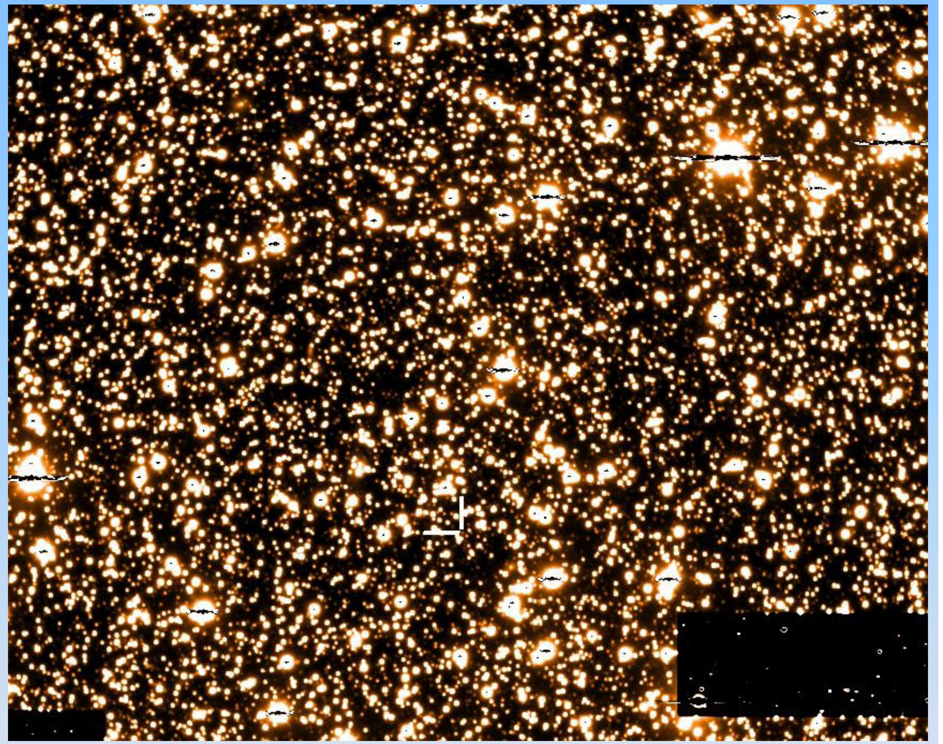
Source name	Spin	Orbital period	When discovered?
SAX J1808.4-3658	401 Hz /2.49 ms	2.01 hrs	April 1998
XTE J1751-305	435 Hz /2.30 ms	0.70 hrs	April 2002
XTE J0929-314	185 Hz /5.41 ms	0.73 hrs	April 2002
XTE J1807-294	191 Hz /5.24 ms	0.67 hrs	Feb 2003
XTE J1814-338	314 Hz /3.18 ms	4.30 hrs	June 2003
IGR J00291-5934	599 Hz /1.67 ms	2.46 hrs	December 2004
HETE J1900.1-2455	377 Hz/2.65 ms	1.39 hrs	June 2005
SWIFT J1756.9-2508	182 Hz/5.49 ms	0.90 hrs	June 2007
Aql X-1	550 Hz/1.82 ms	18.95 hrs	August 2008
SAX J1748.9-2021	442 Hz/2.26 ms	8.77 hrs	August 2008
NGC 6440 X-2	206 Hz/4.85 ms	0.96 hrs	August 2009
IGR J17511-3057	245 Hz/4.08 ms	3.47 hrs	September 2009
Swift J1749.4-2807	518 Hz/1.93 ms	8.82 hrs	April 2010

AMXPs

Source name	Spin	Orbital period	Optical counterpart in quiescence
SAX J1808.4-3658	401 Hz /2.49 ms	2.01 hrs	Y
XTE J1751-305	435 Hz /2.30 ms	0.70 hrs	N
XTE J0929-314	185 Hz /5.41 ms	0.73 hrs	Y
XTE J1807-294	191 Hz /5.24 ms	0.67 hrs	N
XTE J1814-338	314 Hz /3.18 ms	4.30 hrs	Y
IGR J00291-5934	599 Hz /1.67 ms	2.46 hrs	Y
HETE J1900.1-2455	377 Hz/2.65 ms	1.39 hrs	N
SWIFT J1756.9-2508	182 Hz/5.49 ms	0.90 hrs	N
Aql X-1	550 Hz/1.82 ms	18.95 hrs	Y
SAX J1748.9-2021	442 Hz/2.26 ms	8.77 hrs	N
NGC 6440 X-2	206 Hz/4.85 ms	0.96 hrs	N
IGR J17511-3057	245 Hz/4.08 ms	3.47 hrs	N
Swift J1749.4-2807	518 Hz/1.93 ms	8.82 hrs	N

Hard targets…



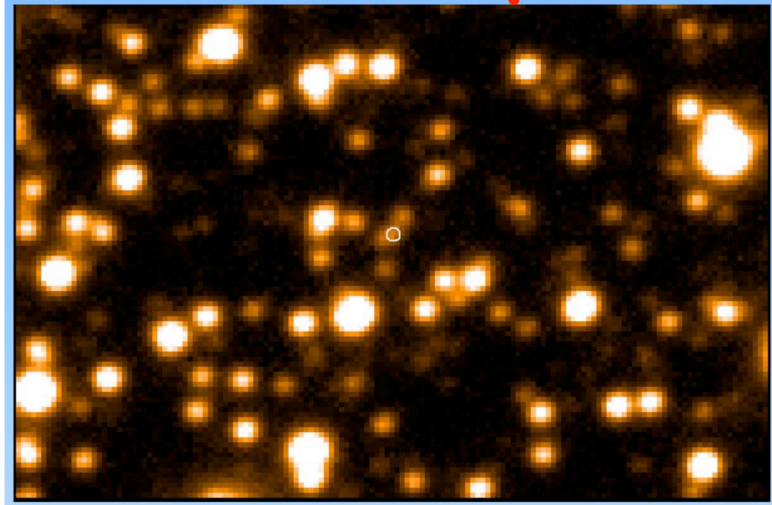


High interstellar absorption, crowded fields, intrinsic faintness

2002-2007 observational campaign

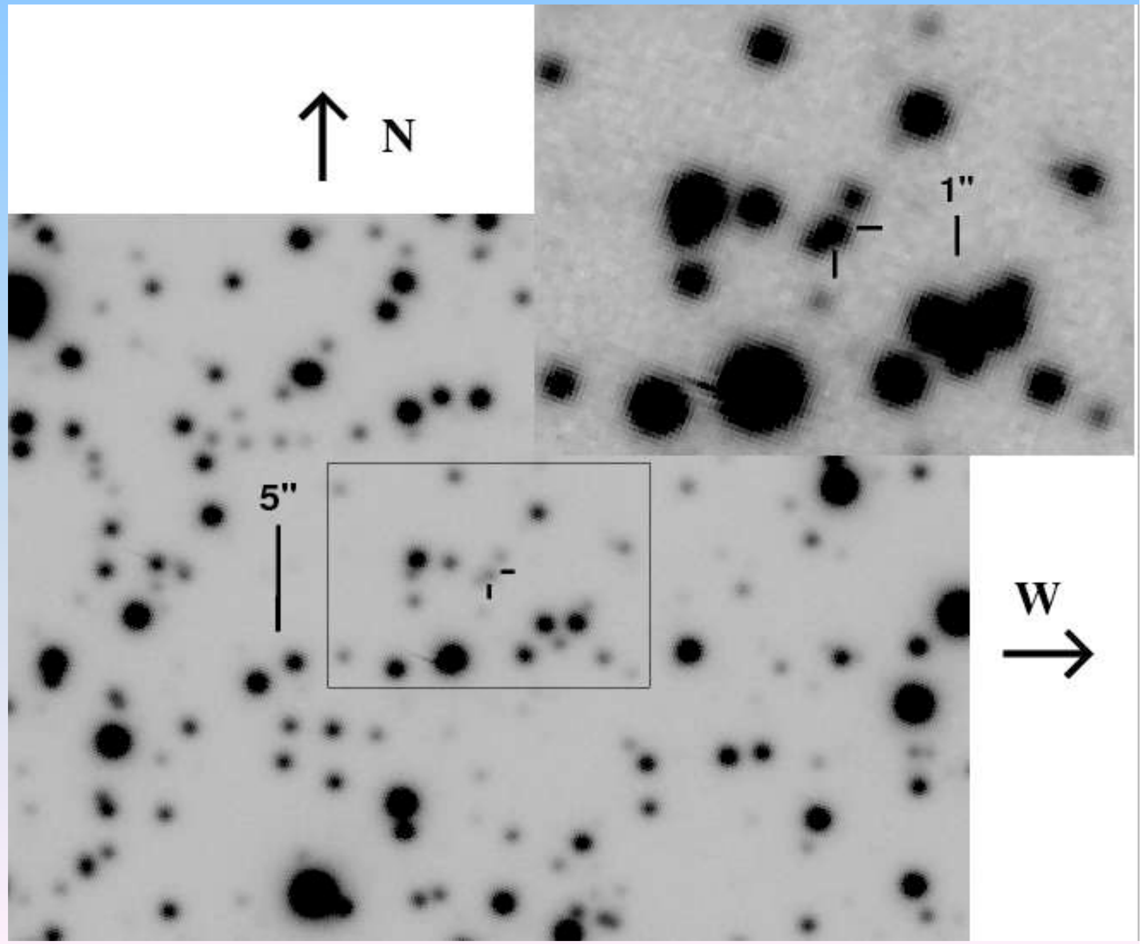
SAX J1808.4-3658: the optical counterpart

P_{orb} ~ 2.0 hrs
P_{spin} ~ 2.5 ms

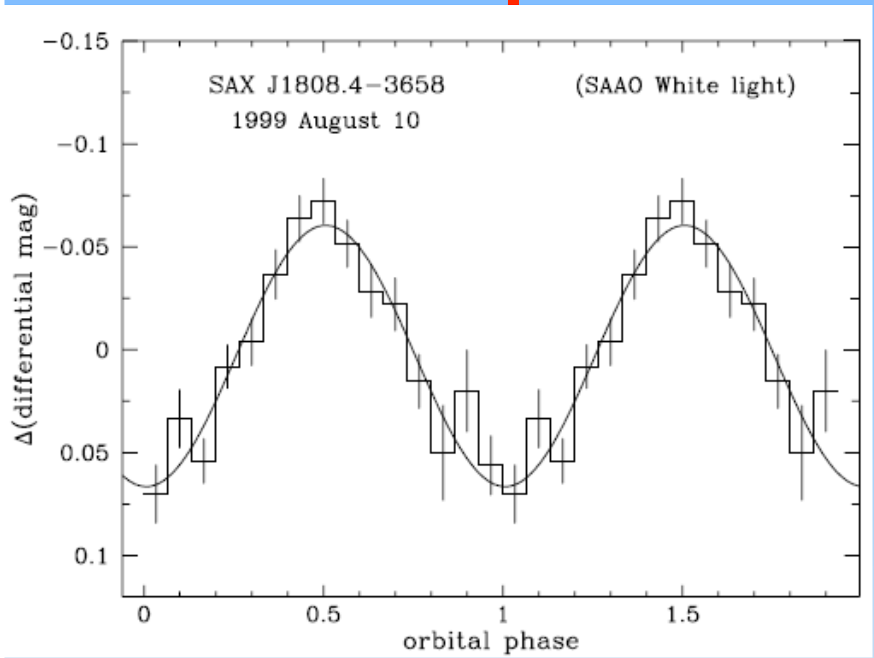


VLT+FORS2
R-band image

(Homer et al. 2001,
Burderi et al. 2003,
Campana et al. 2004,
Deloye et al. 2008,
Wang et al. 2009)



SAX J1808.4-3658: the optical counterpart



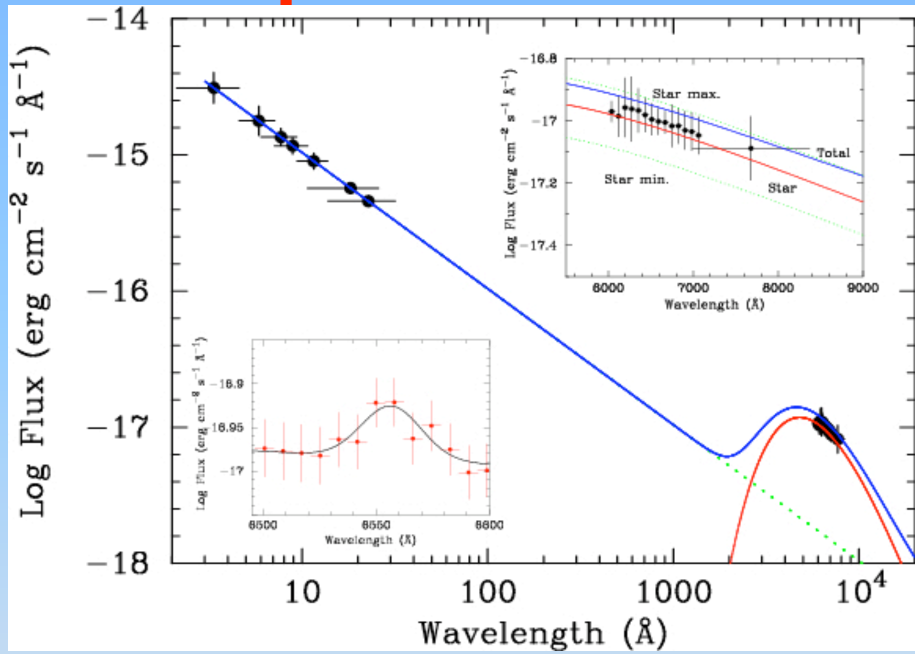
minimum in the optical light curve when the NS is behind the companion

(Homer et al. 2001,

Campana et al. 2004,

Deloye et al. 2008

Wang et al. 2009)



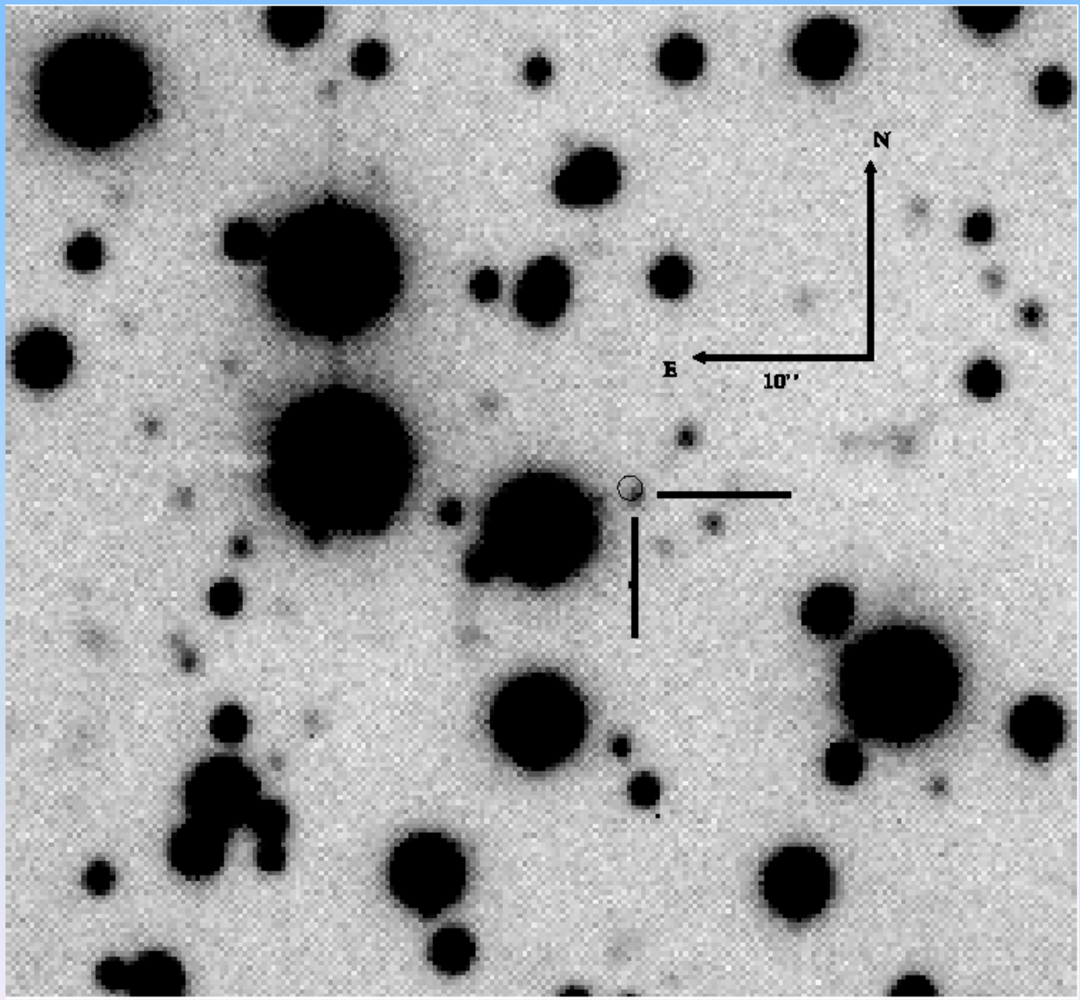
$L_{irr} = 4 \times 10^{33}$ erg/s >> $L_X = 10^{31}$ erg/s

indirect evidence of an active ms radio pulsar

$B \sim 6 \times 10^{7}$ G

(Burderi et al. 2003, Campana et al. 2004, Deloye et al. 2008, Wang et al. 2009)

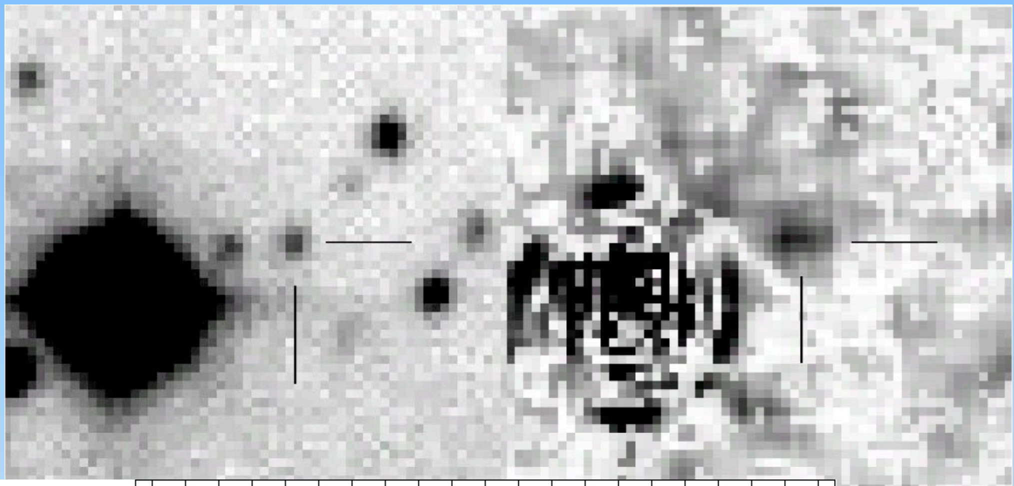
IGR J00291+5934: the optical/NIR counterpart

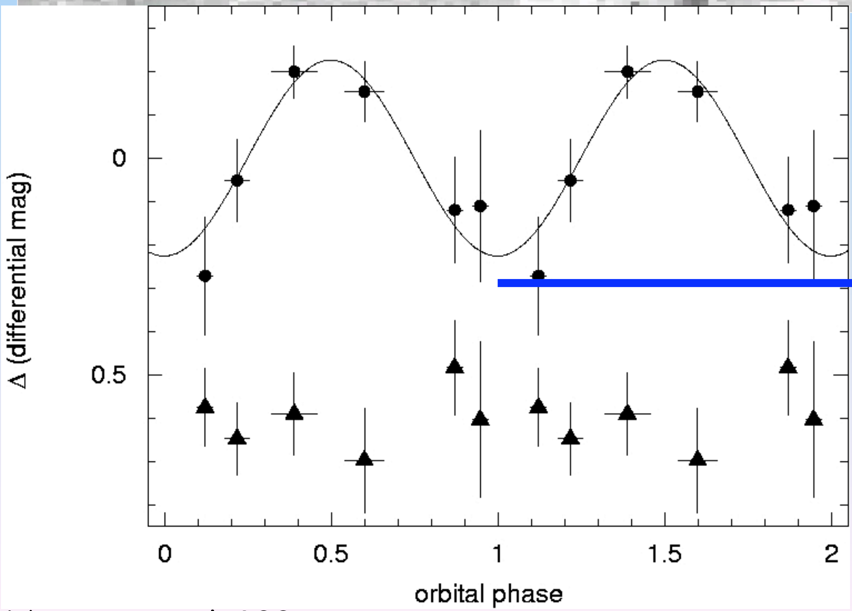


TNG+doLoReS *R*-band image (Aug 2005)

see also Torres et al. 2008; Jonker et al. 2008

IGR J00291+5934: the optical light curve





D'Avanzo et al. 2007

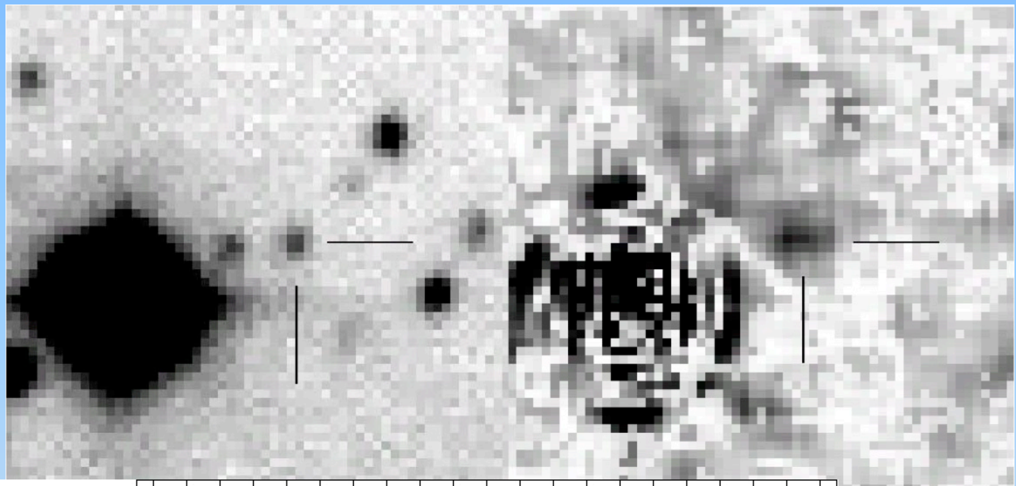
P_{orb} ~ 2.5 hrs
P_{spin} ~ 1.7 ms

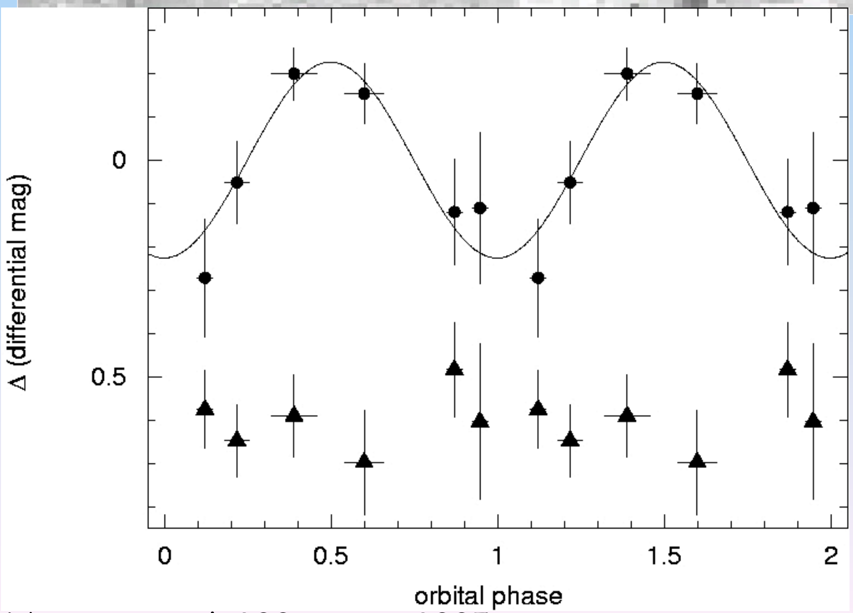
Sinusoidal light curve modulated at the 2.46 hrs orbital period

Minimum when the NS is behind the companion

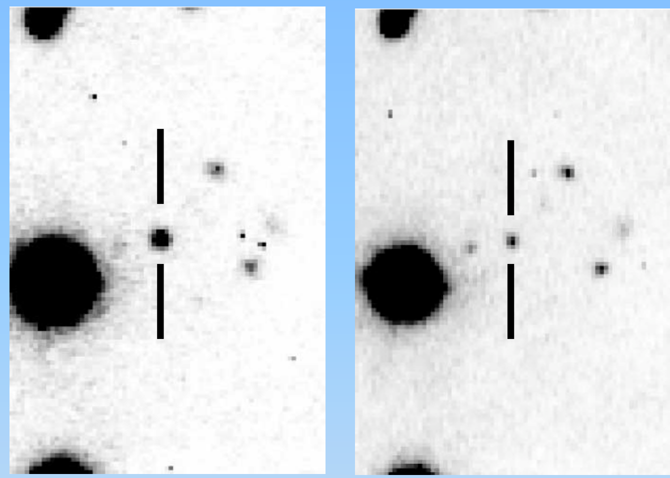
Same lc in SAX J1808.4-3658

IGR J00291+5934: the optical light curve

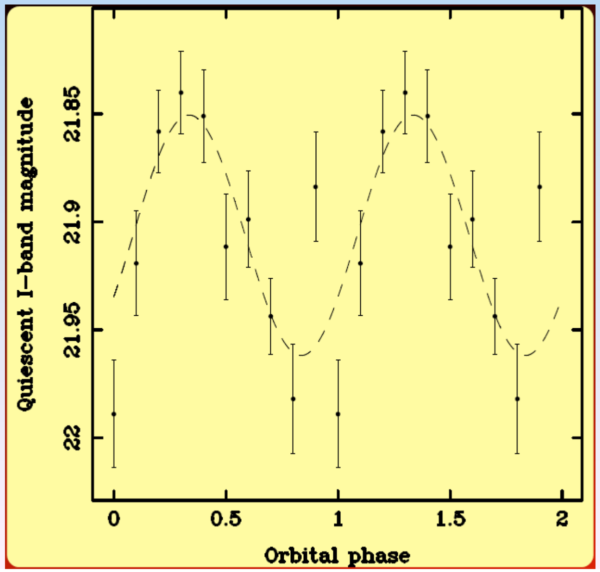




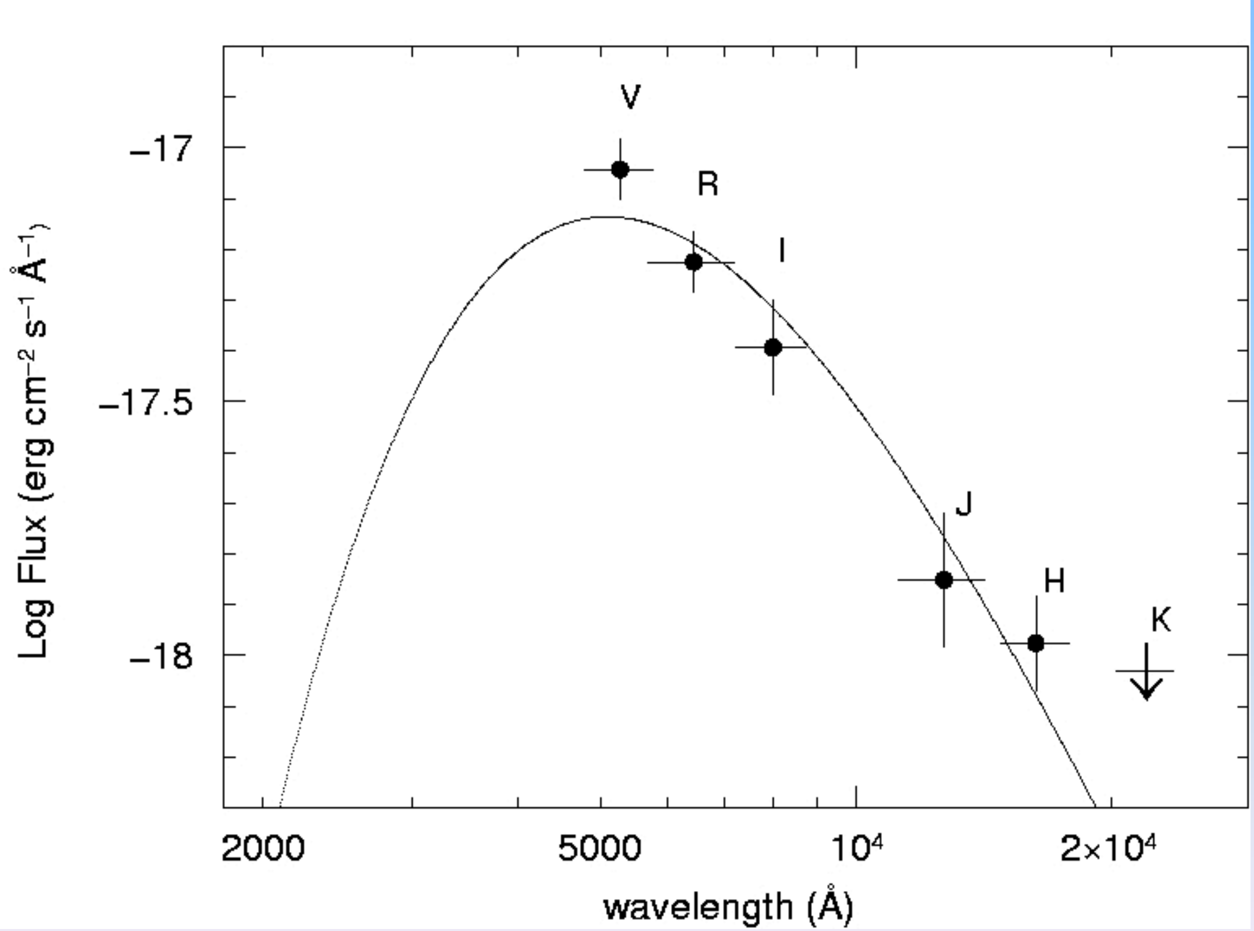
D'Avanzo et al. 2007; Sept 2005



Jonker et al. 2008 (Sept. 2006)



IGR J00291+5934: possible sources of quiescent optical emission



B ~ 9.7 x 10^7 G

L_{irr} = 4 - 5 x 10^{33} erg/s

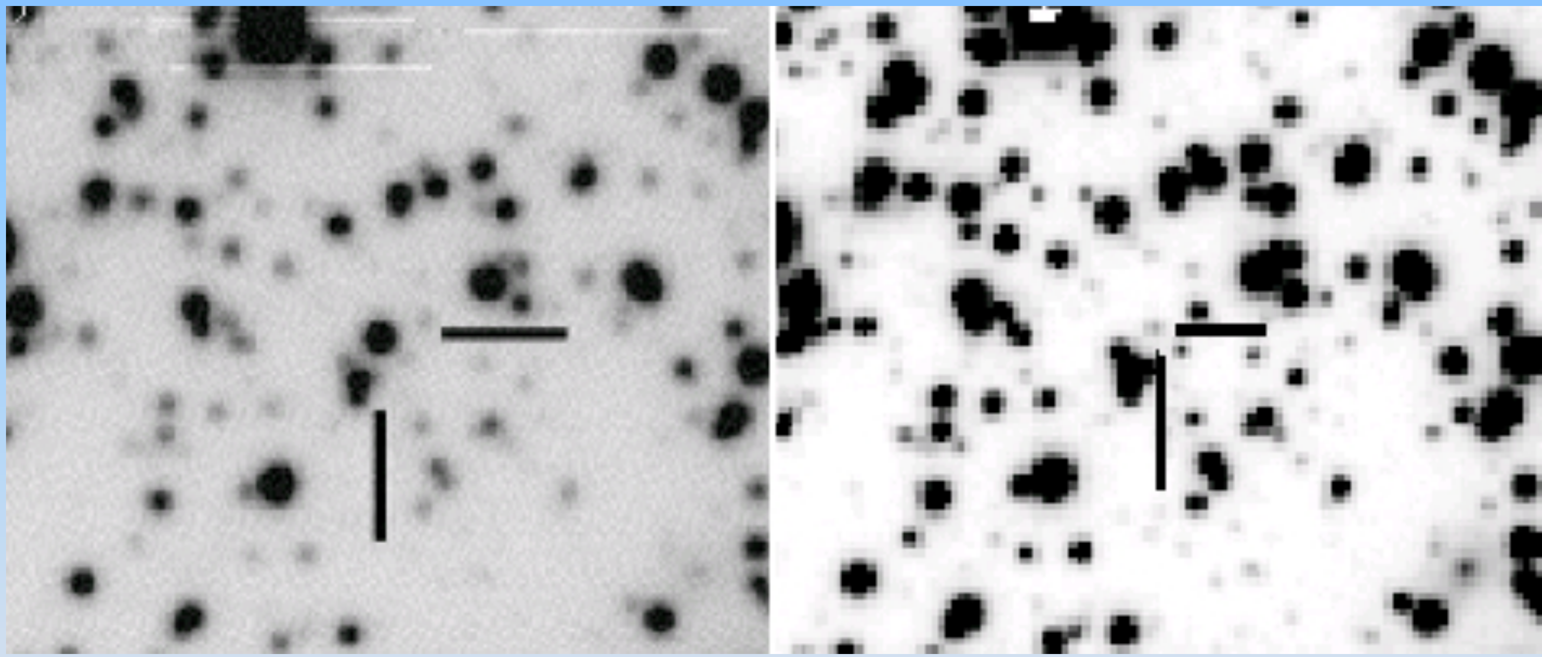
vs.

L_X = 8 x 10^{31} erg/s

Reminiscent of SAX J1808.4-3658

D'Avanzo et al. 2007

XTE J1814-338: the optical counterpart

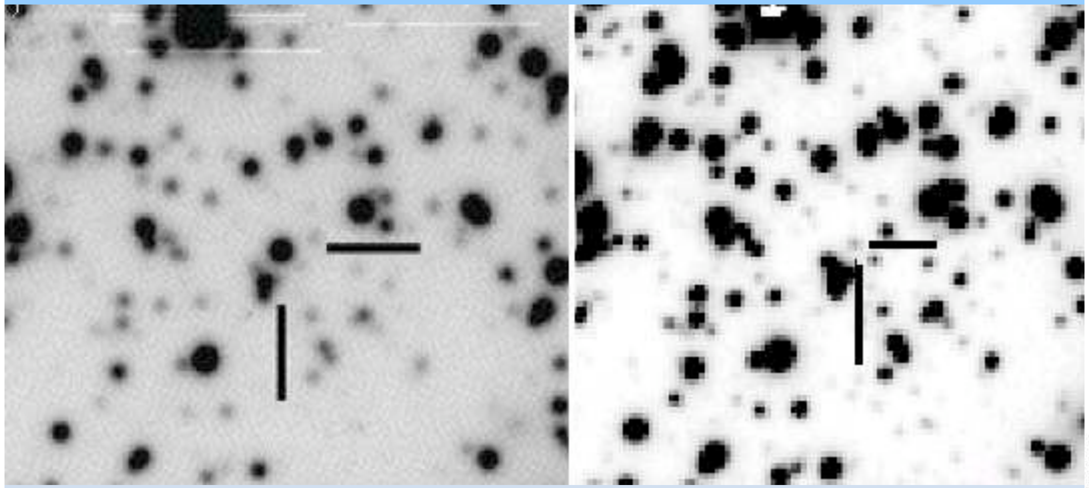


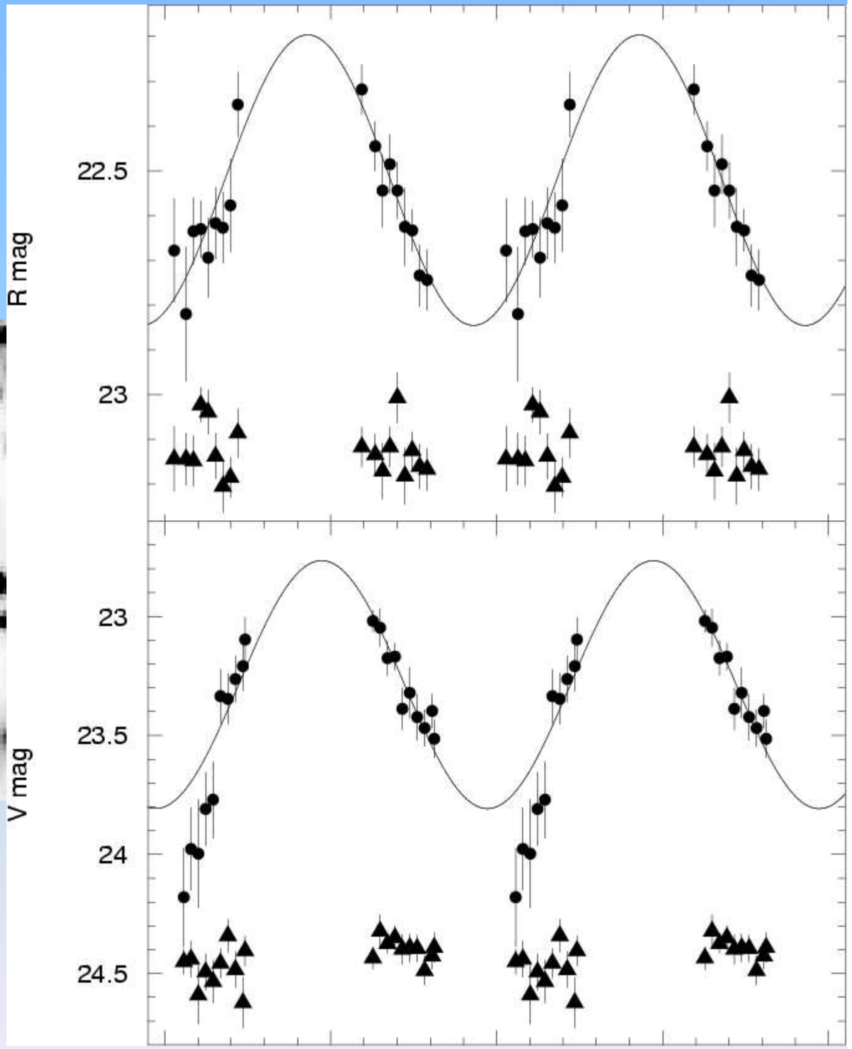
Krauss et al. (2005)

VLT+FORS2
R-band image

XTE J1814-338: a puzzling light curve

P_{orb} ~ 4.3 hrs
P_{spin} ~ 3.2 ms





D'Avanzo et al. 2009

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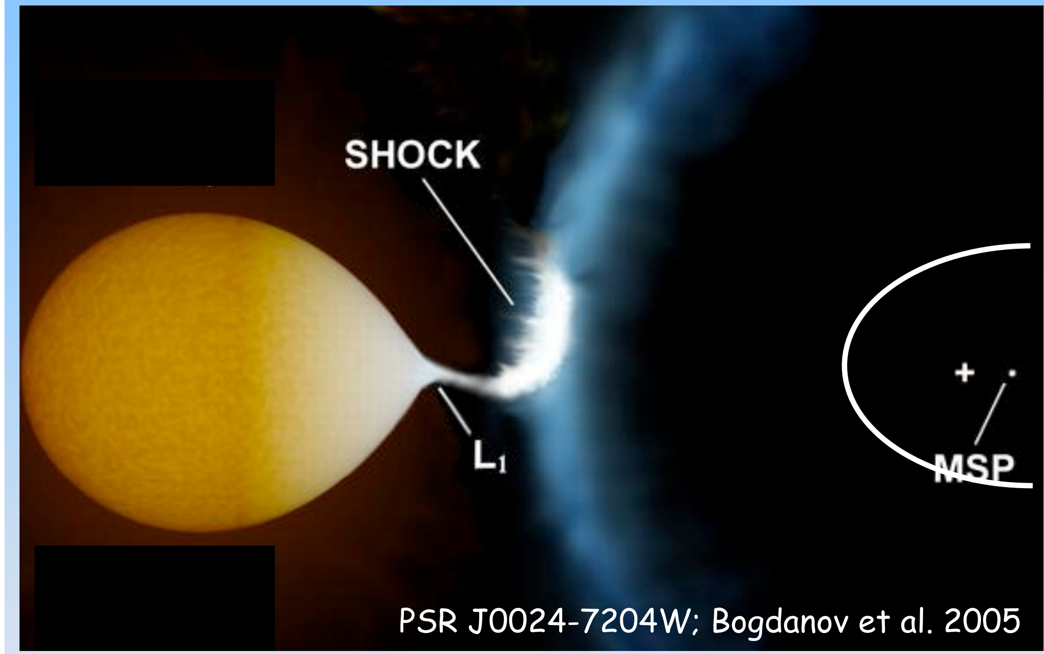
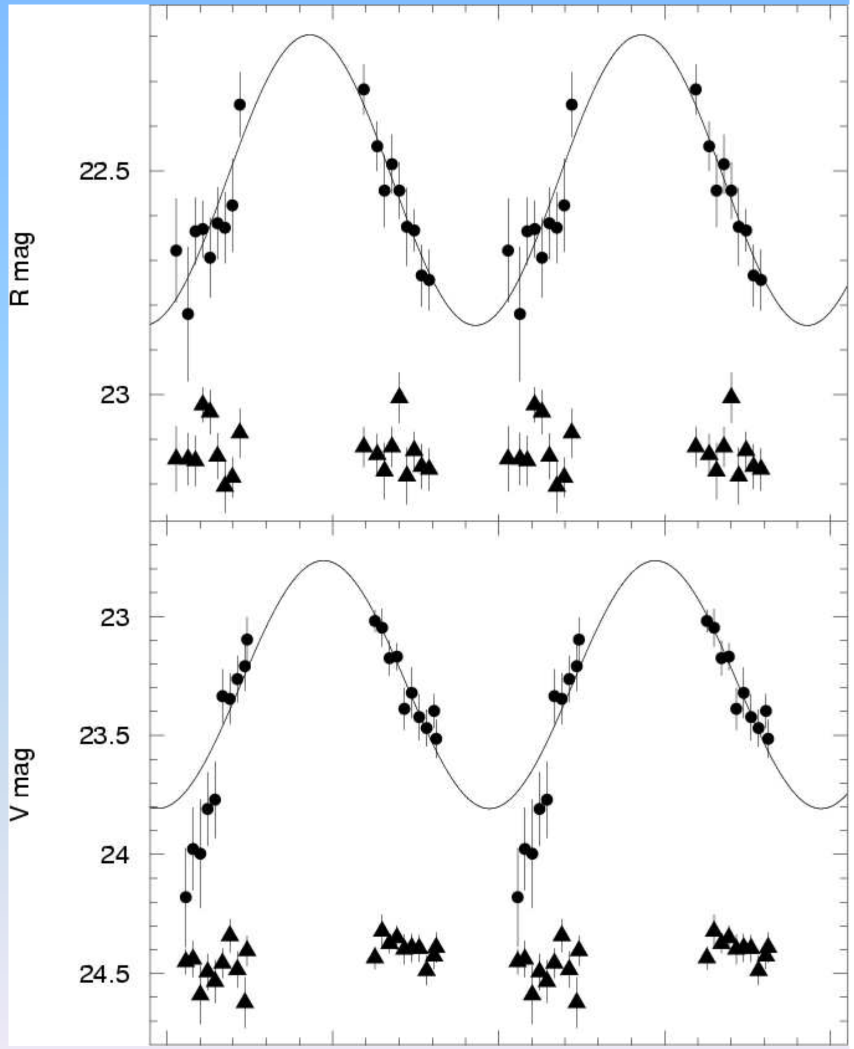




Assuming a symmetric "eclipse" around phase 0:
$1.0\ R_{SUN}$ < *eclipsing region* < $3.0\ R_{SUN}$

No X-ray eclipses or dips (*i* < 77°; Krauss et al. 2005)

D'Avanzo et al. 2009

XTE J1814-338: possible sources of quiescent optical emission

L_{irr} (erg s^{-1})
$(1.00 \pm 0.04) \times 10^{34}$

vs.

$L_X < 10^{32}$ erg/s

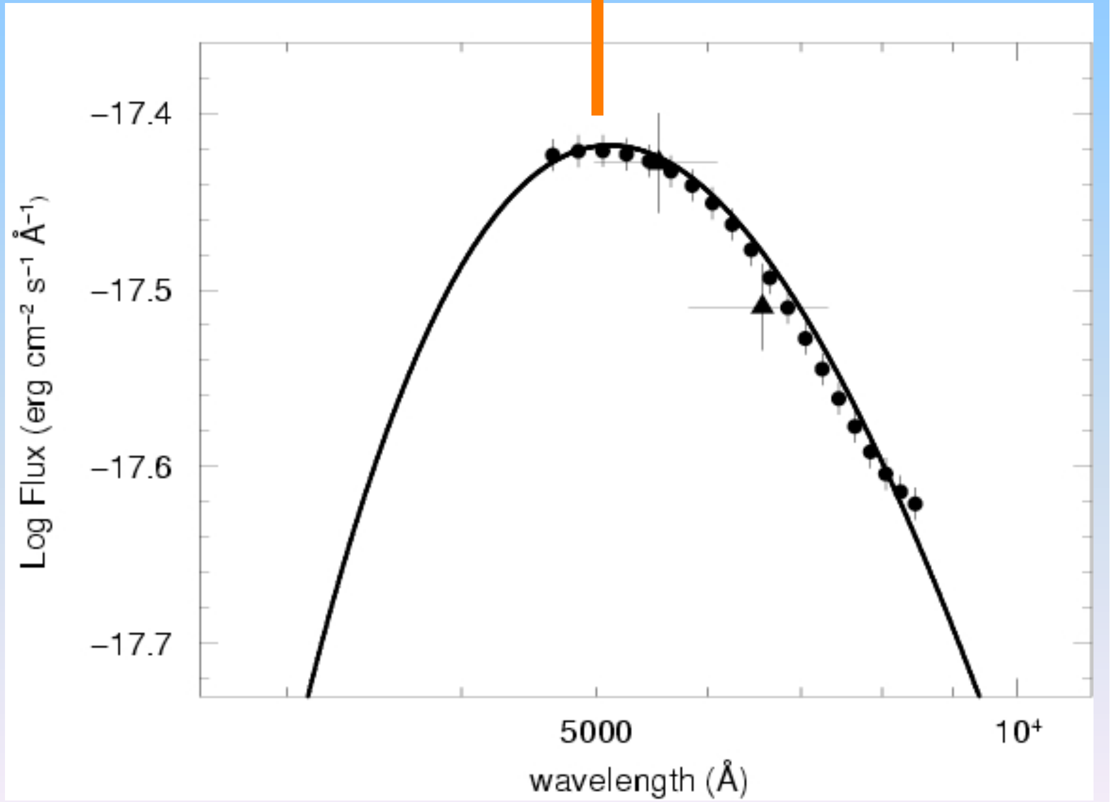
B ~ 6 x 10^7 G

$M_c = 0.23 \pm 0.08\ M_{Sun}$

M-type star

$T \sim 5700$ K

G-type star



D'Avanzo et al. 2009

AMXPs

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Aql X-1	550 Hz/1.82 ms	18.95 hrs	Y
SAX J1748.9-2021	442 Hz/2.26 ms	8.77 hrs	N
NGC 6440 X-2	206 Hz/4.85 ms	0.96 hrs	N
IGR J17511-3057	245 Hz/4.08 ms	3.47 hrs	N
Swift J1749.4-2807	518 Hz/1.93 ms	8.82 hrs	N

ultracompact AMXPs: companion stars

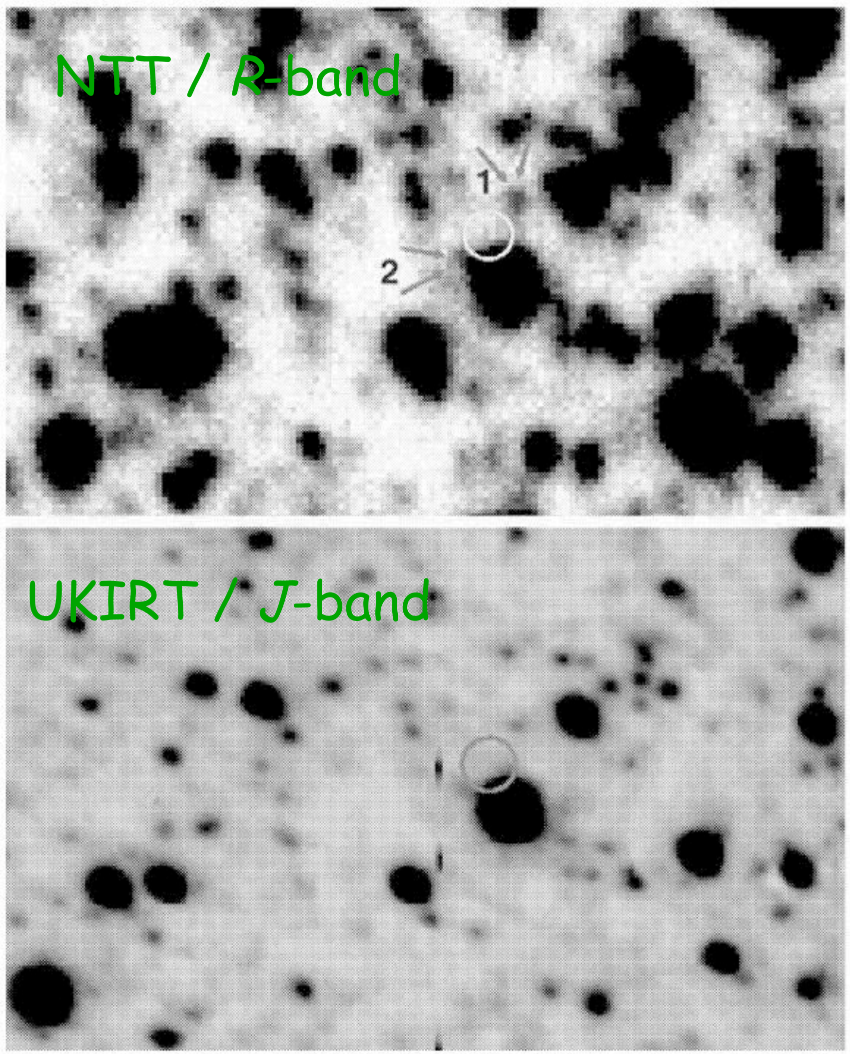
Possible companion stars in binary systems with P_{orb} < 80 min

Hydrogen | **no Hydrogen**

extremely evolved MS star
(or He-burning star)
(Nelson et al. 1986;
Fedorova & Ergma 1989;
Podsiadlowski et al. 2002;
Nelson & Rappaport 2003)

He or C/O WD
(Bildsten 2002;
Deloye & Bildsten 2003)

XTE J1751-305: the optical counterpart

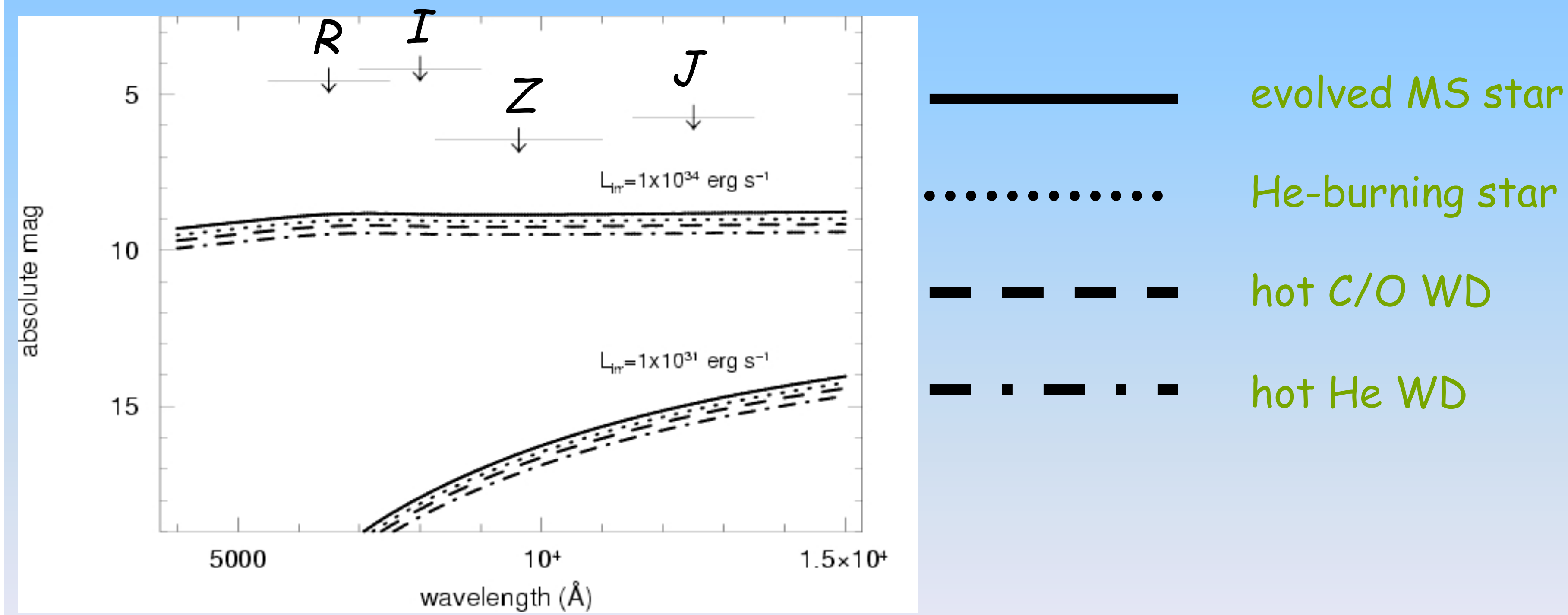


Jonker et al. 2003, MNRAS, 344, 201

$R > 23.1$ (3σ)
$I > 21.6$ (3σ)
$Z > 20.6$ (3σ)
$J > 19.5$ (3σ)

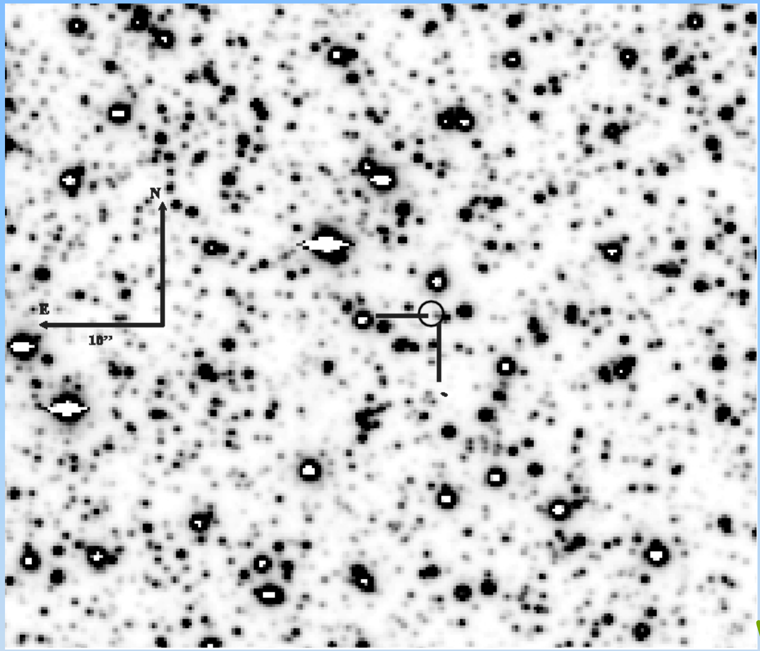
$E(B-V) = 1.7$, $A_V = 4.0$

XTE J1751-305: the companion star



D'Avanzo et al. 2009

XTE J1807-294: the optical counterpart?

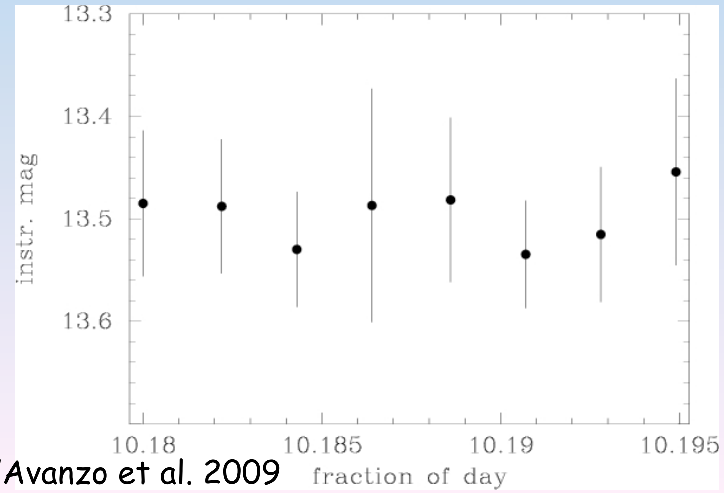


VLT+FORS1
R-band image

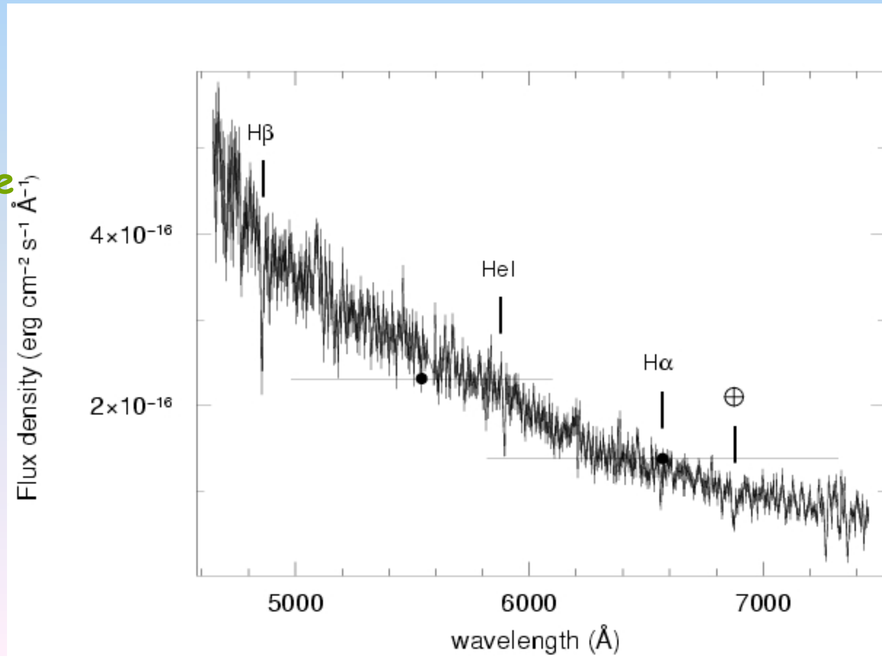
$V = 22.11 \pm 0.05$
$R = 21.37 \pm 0.07$

$V > 24.3$ (3σ)
$R > 24.2$ (3σ)
$J > 19.7$ (3σ)

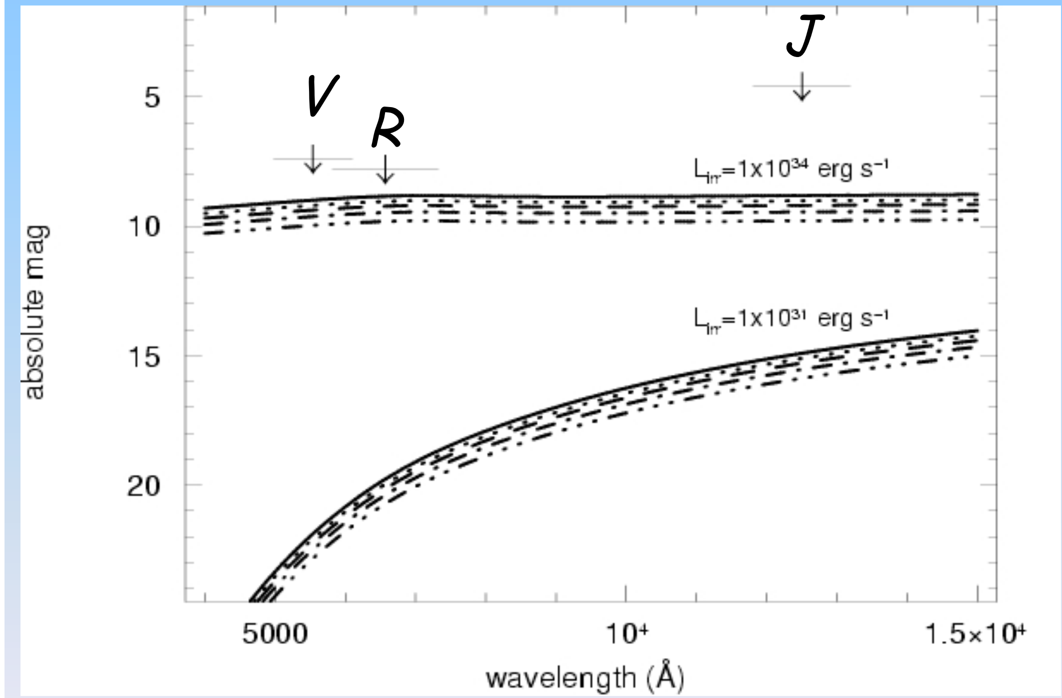
$E(B-V) = 0.8$, $A_V = 2.4$



D'Avanzo et al. 2009



XTE J1807-294: the companion star



evolved MS star

He-burning star

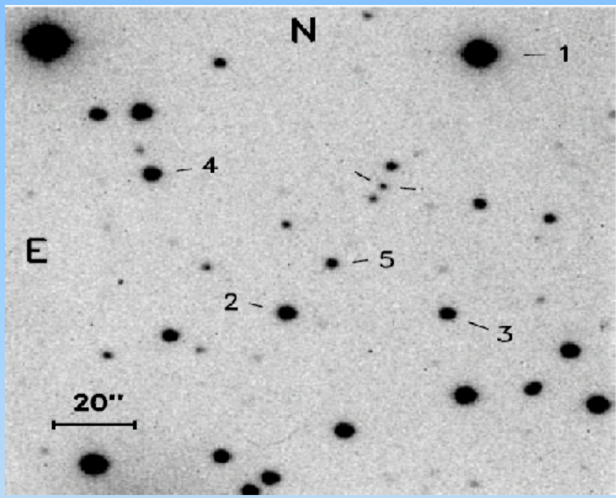
hot C/O WD

hot He WD

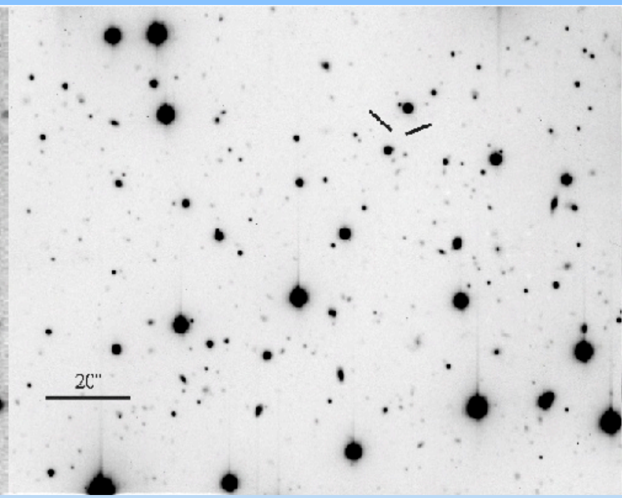
cold He WD

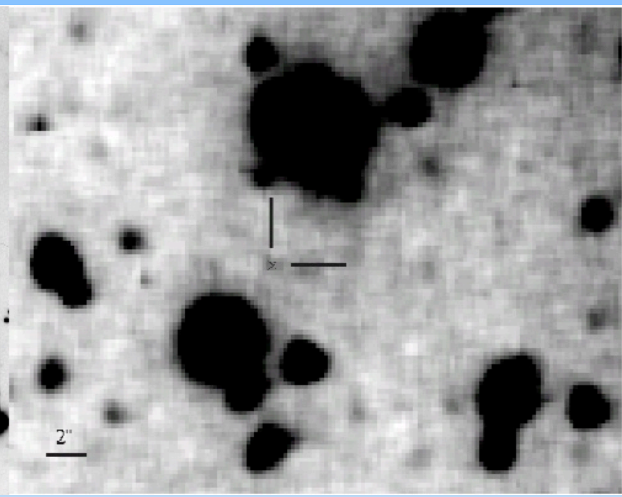
D'Avanzo et al. 2009

XTE J0929-314: the optical counterpart



I-band image
(Giles et al. 2005)





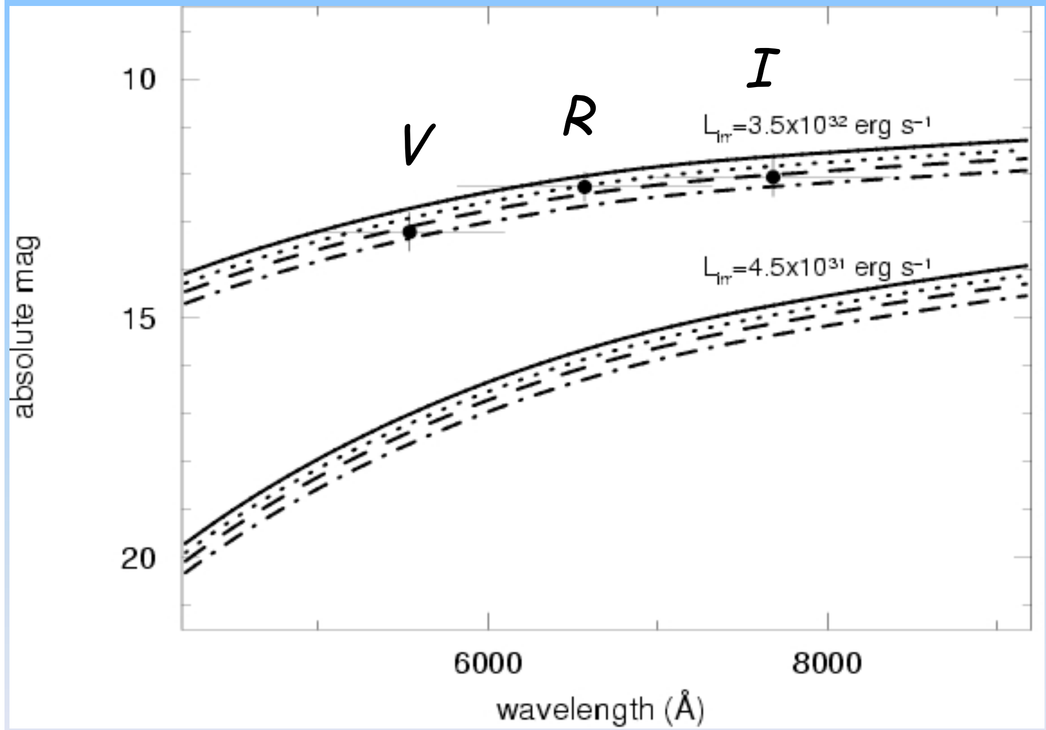
VLT+FORS1
I-band image

(Monelli et al. 2005;
D'Avanzo et al. 2009)

$V = 28.2 \pm 0.4$
$R = 27.1 \pm 0.3$
$I = 26.9 \pm 0.4$

$E(B-V) = 0.2$, $A_V = 0.5$

XTE J0929-314: the companion star



- evolved MS star
- He-burning star
- hot C/O WD
- hot He WD

$L_{irr} \sim 3.5 \times 10^{32}$ erg/s >> $L_X = 4.5 \times 10^{31}$ erg/s

$B \sim 1.8 \times 10^{8}$ G

D'Avanzo et al. 2009

ultracompact AMXPs: companion stars

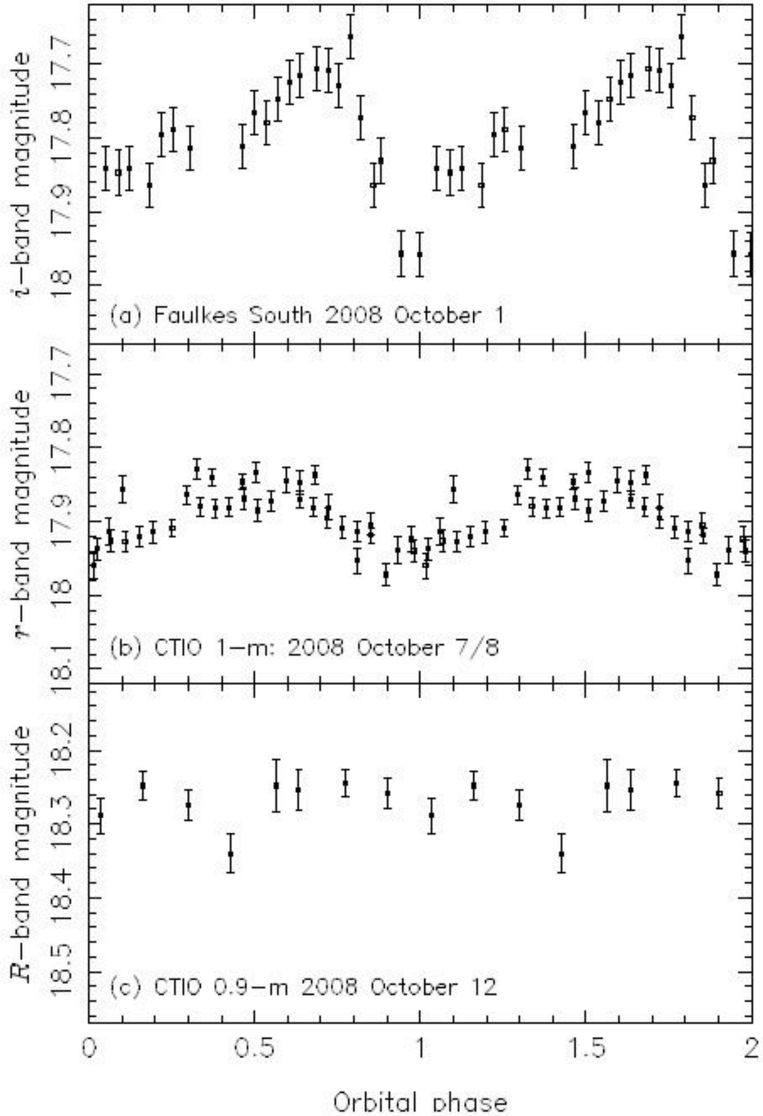
- as for compact AMXPs, the companion stars in ultracompact systems are highly irradiated
- with our data we cannot distinguish between the proposed models for the companion stars

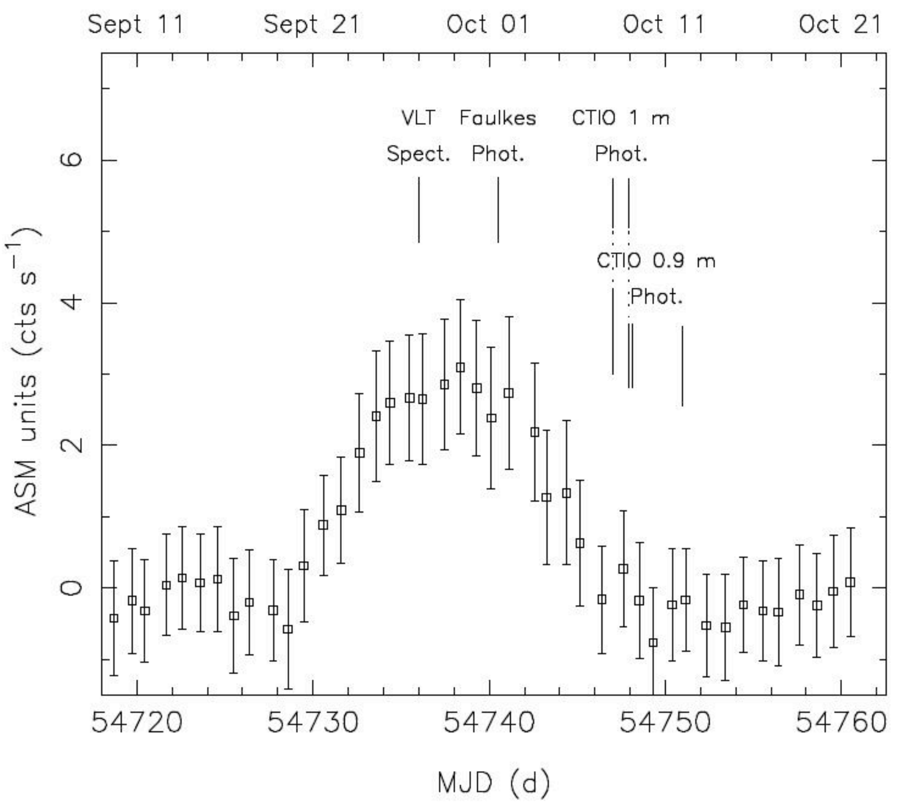
BUT...

- at variance with compact systems, ultracompact AMXPs do not show type I X-ray bursts (i.e. Hydrogen/Helium ignition on the NS surface; Maraschi & Cavaliere 1977; Woosley & Taam 1976)
- no hydrogen lines in ultracompact AMXPs spectra

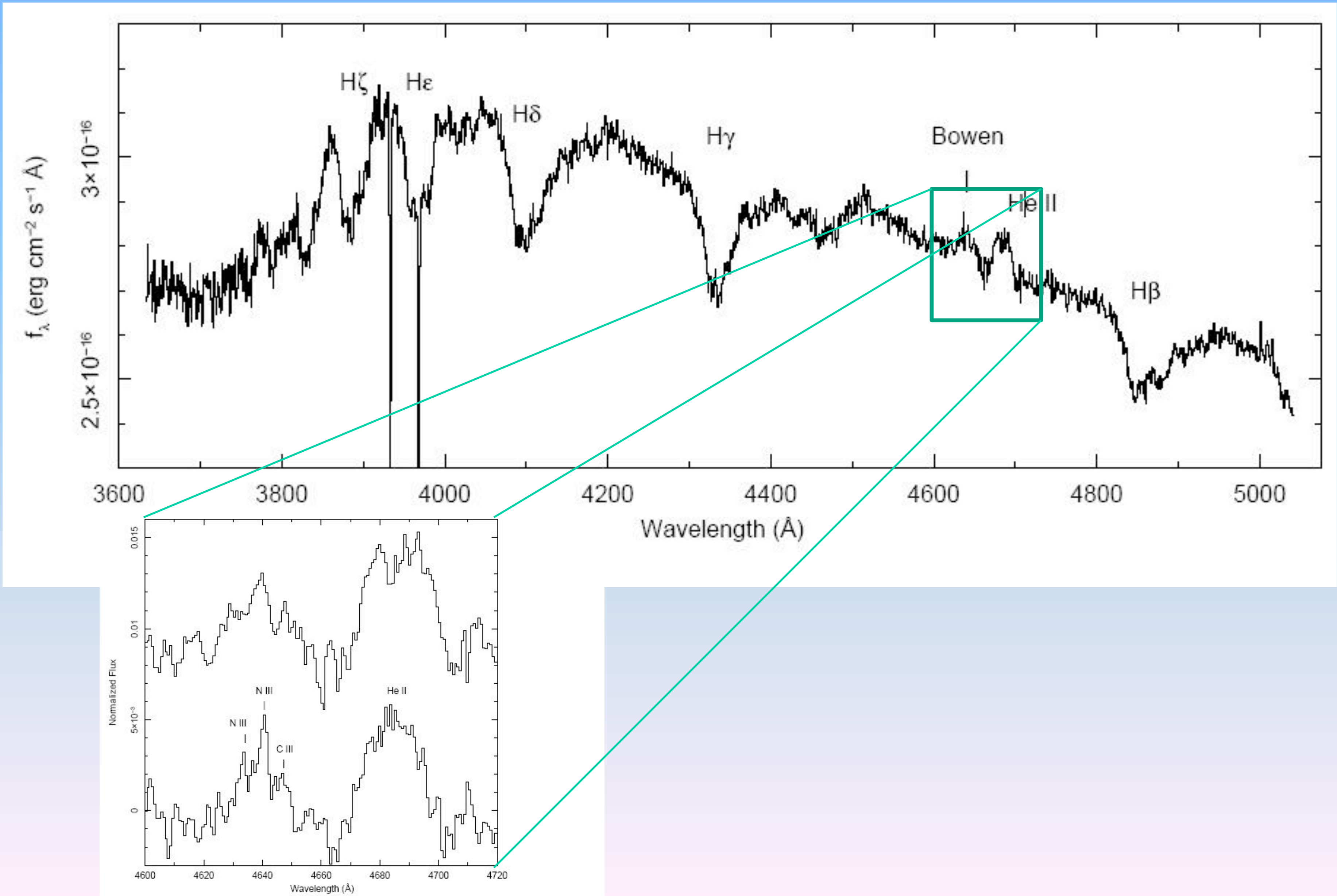
WD scenario

SAX J1808.4-3658: 2008 outburst

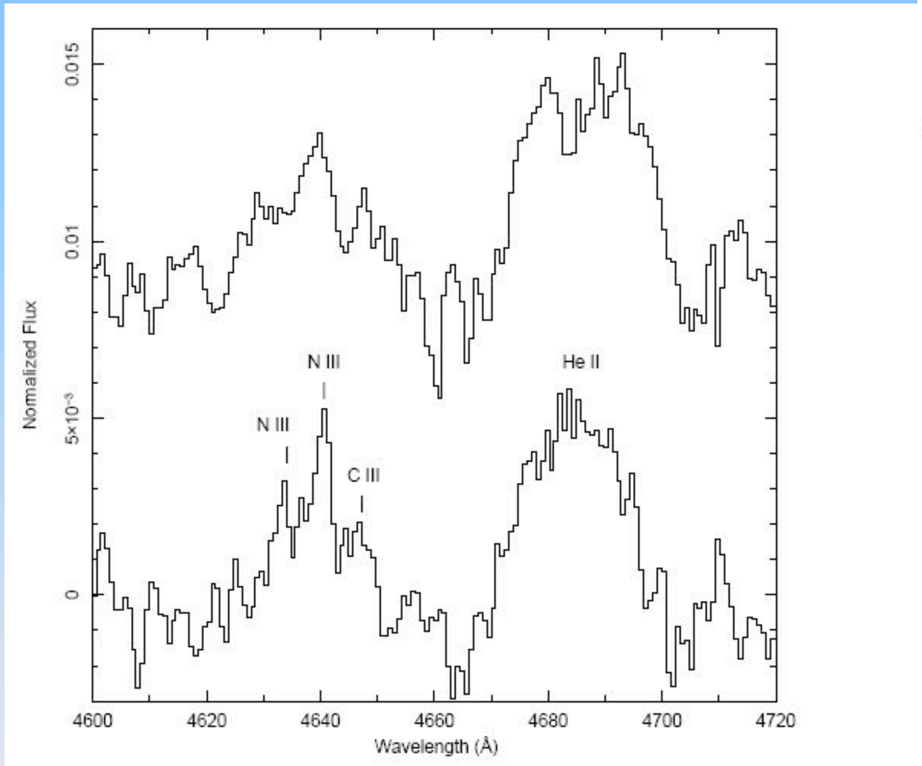


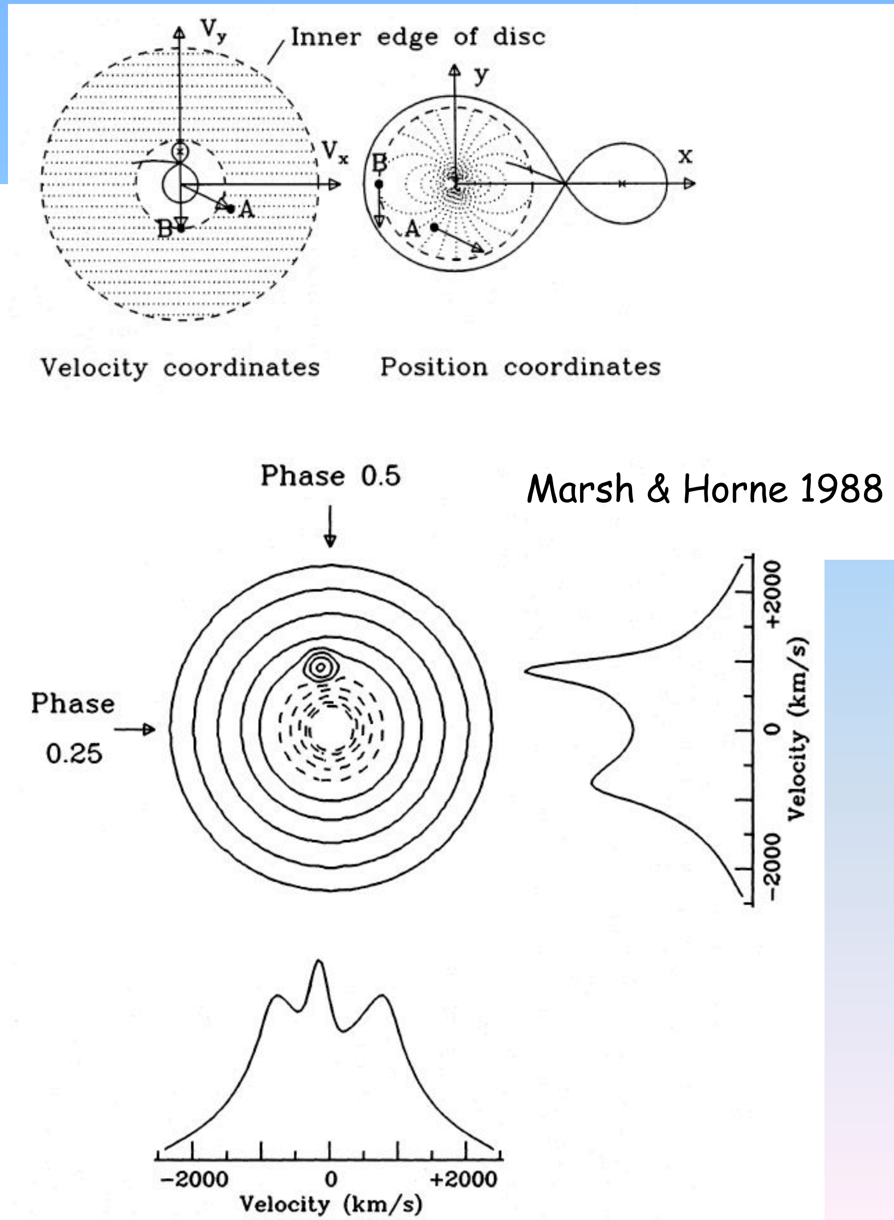


SAX J1808.4-3658: VLT spectroscopy



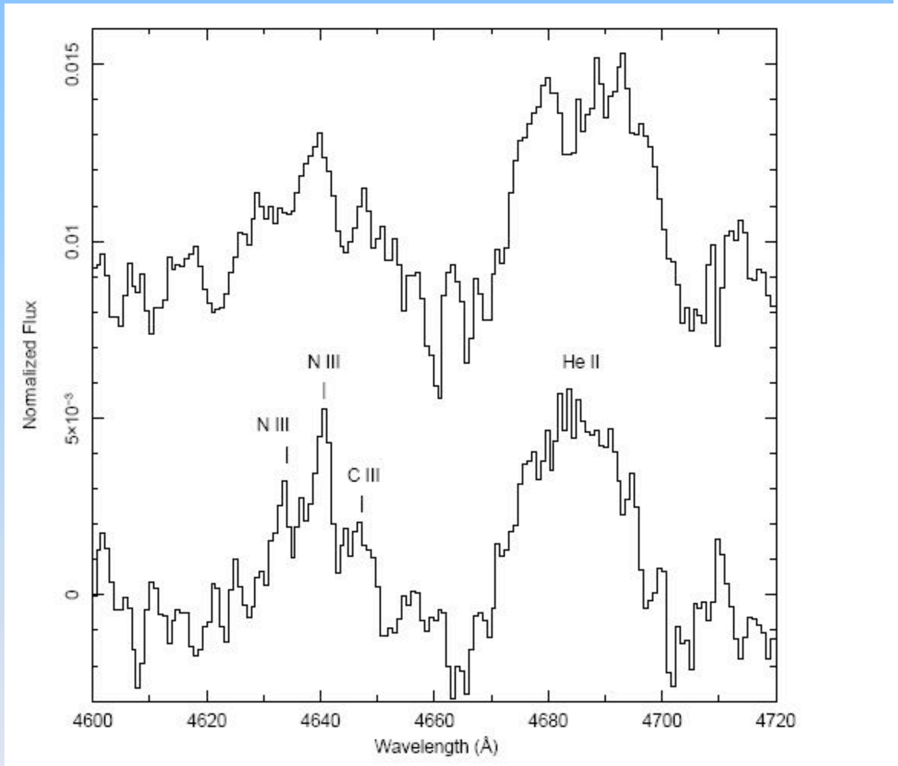
SAX J1808.4-3658: Doppler maps

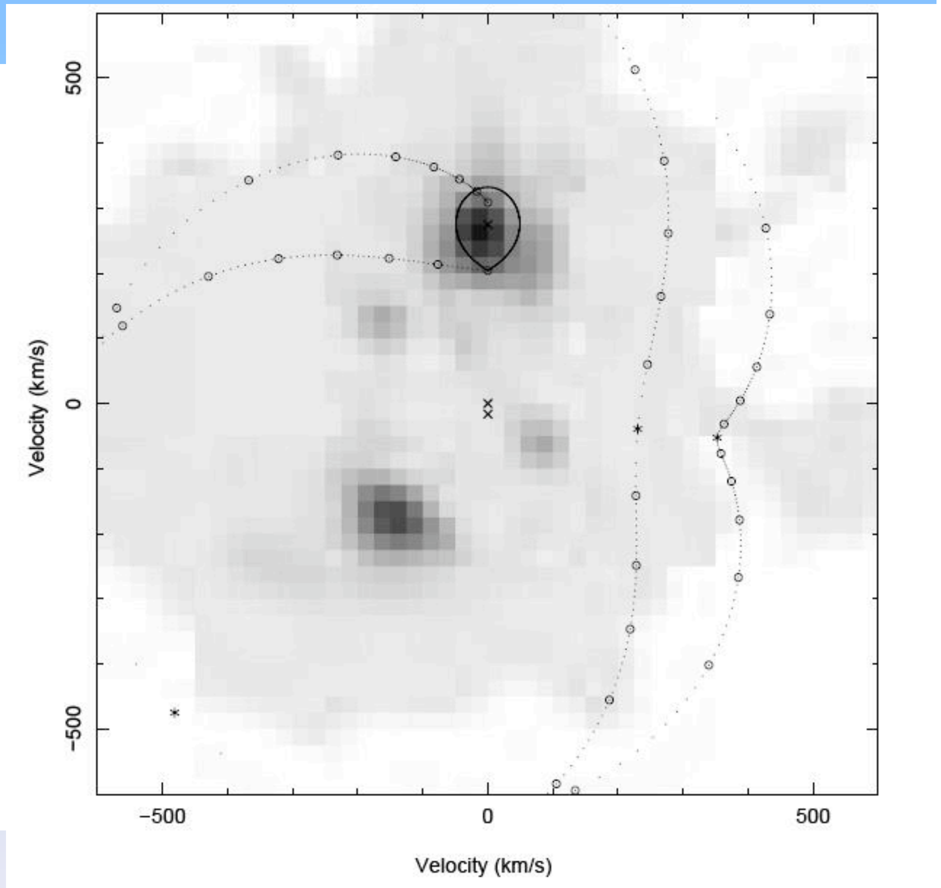




Marsh & Horne 1988

SAX J1808.4-3658: Doppler maps





SAX J1808.4-3658: mass estimate

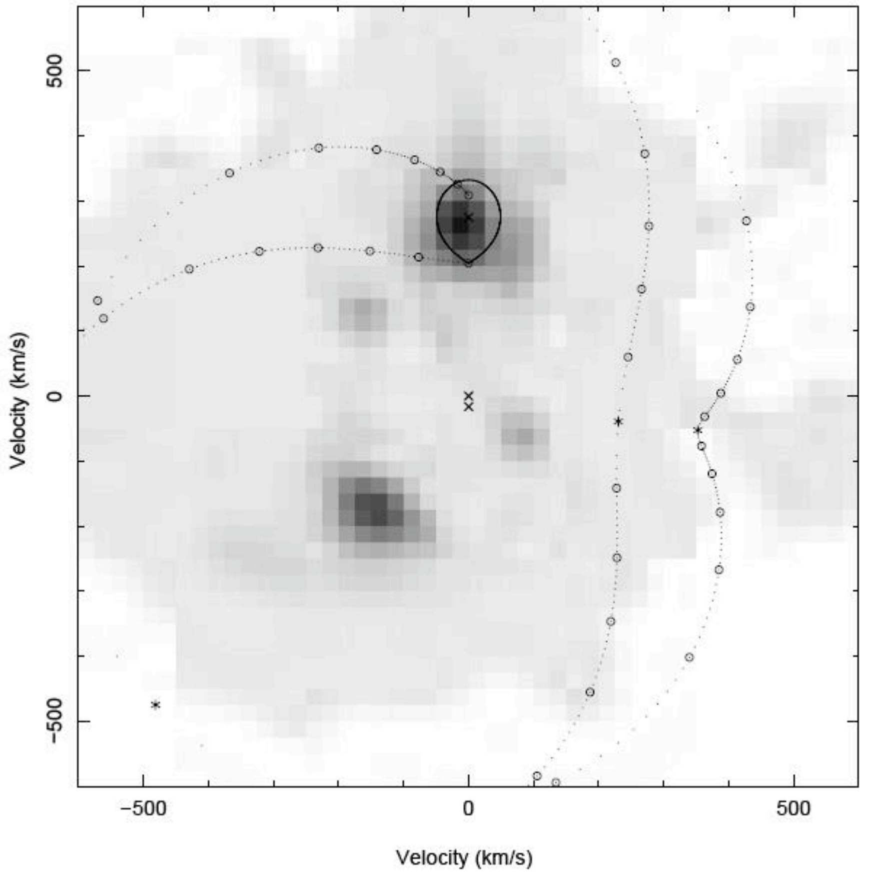
$$f(M) = \frac{M_1 \sin^3 i}{(1+q)^2} = \frac{K_2^3 P_{\rm orb}}{2\pi G} = \frac{K_1^3 P_{\rm orb}}{2\pi G q^3}$$

$228 < K_2 < 322$ km/s

$0.051 < q < 0.072$

$36° < i < 67°$ (Deloye et al. 2008)

$0.15\ M_{SUN} < M_X < 1.58\ M_{SUN}$



Cornelisse, D'Avanzo, Muñoz Darias et al. 2009

SAX J1808.4-3658: mass estimate

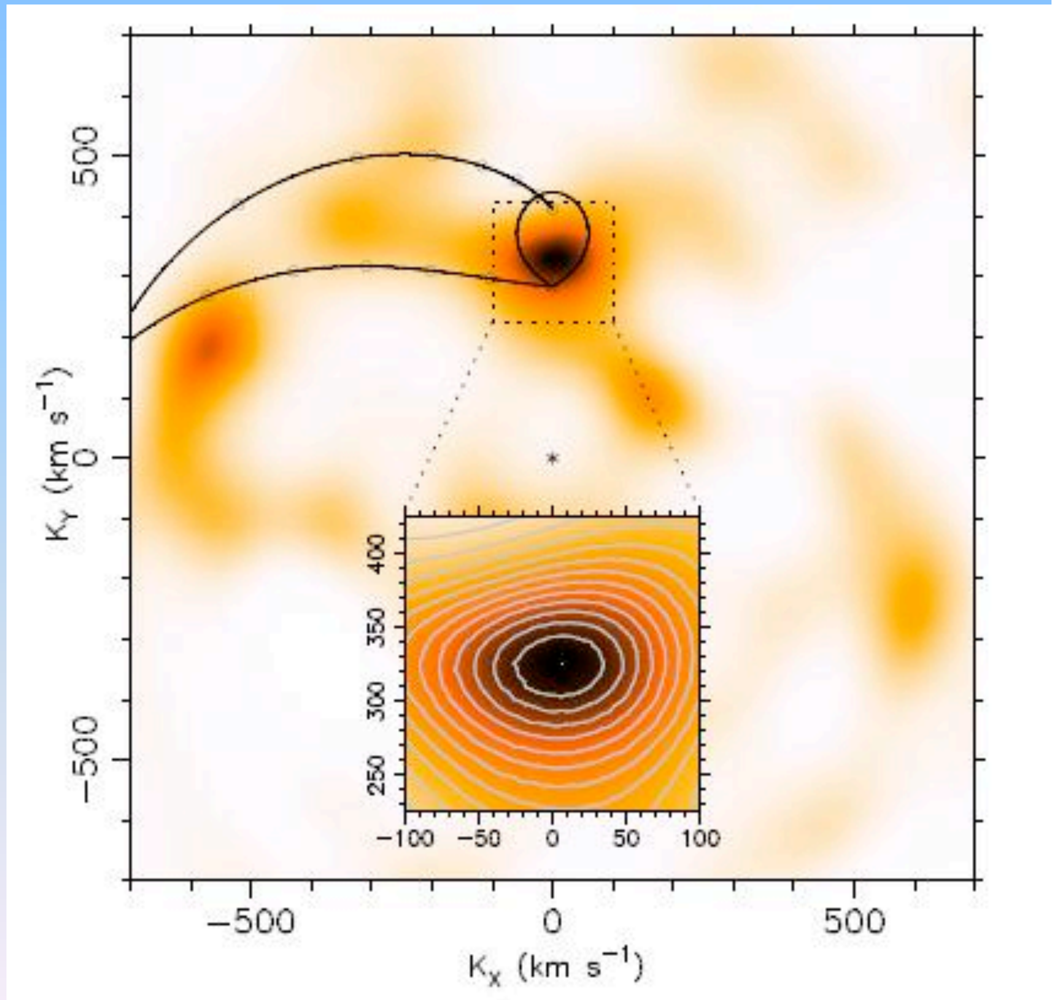
(Elebert et al. 2009)

$330 < K_2 < 410$ km/s

$0.040 < q < 0.049$

$36° < i < 67°$ (Deloye et al. 2008)

$0.6\ M_{SUN} < M_X < 1.8\ M_{SUN}$



Conclusions

- **Accreting Millisecond X-ray Pulsars:**
  - first comprehensive study of the optical counterparts in quiescence
  - evidence of highly irradiated companion stars
  - weak (~10^8 G) NS magnetic fields
  - indirect evidence of an active ms radio pulsar
  - no H in ultracompact systems: WD companions

  - Next: NS mass estimates through radial velocity measurements