Millisecond Pulsar Binaries at Transition

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Observational Studies of Compact Star Systems

Galactic Compact Stars

X-Ray binaries (Structure, emission properties and evolution)

Debris Disks around compact stars （formation of planetary systems and evolution）

Fermi Gamma-ray sources （identification and emission properties）

- Using different telescopes, ground-based and space-based, and focusing mostly on high-energy objects

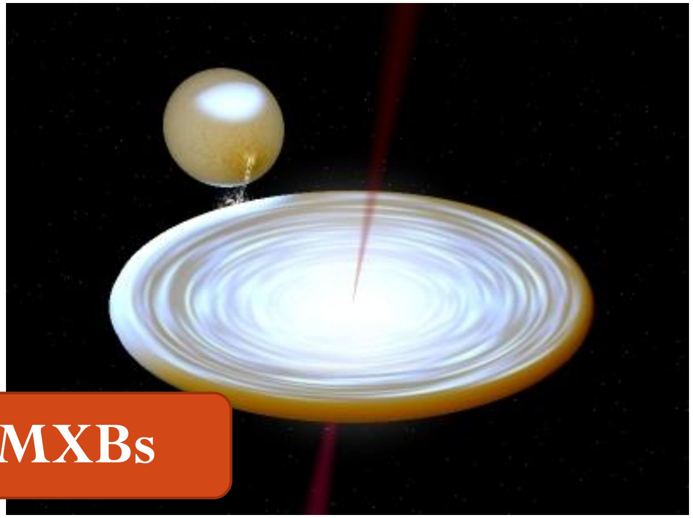
Outline

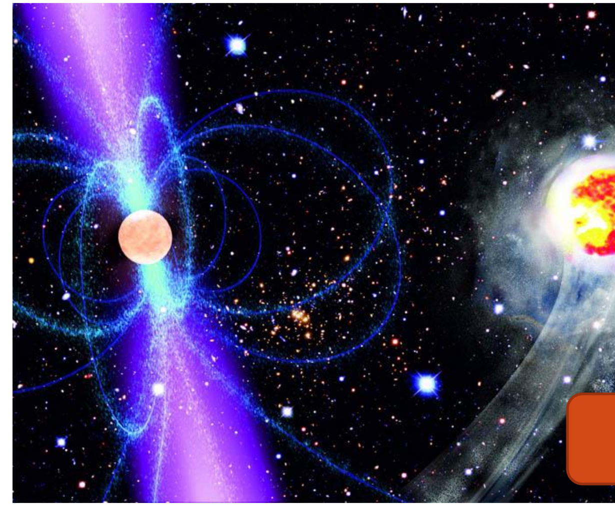
1. Background: accreting pulsar binaries and millisecond pulsar (MSP) binaries
2. Multi-wavelength properties of the transitional MSP binary J1023+0038
   - The Accretion state in 2001
   - The 2^{nd} transition of J1023+0038 in 2013 June
3. The second such binary XSS J12270-4859
4. Speculation and Possibility
5. Summary

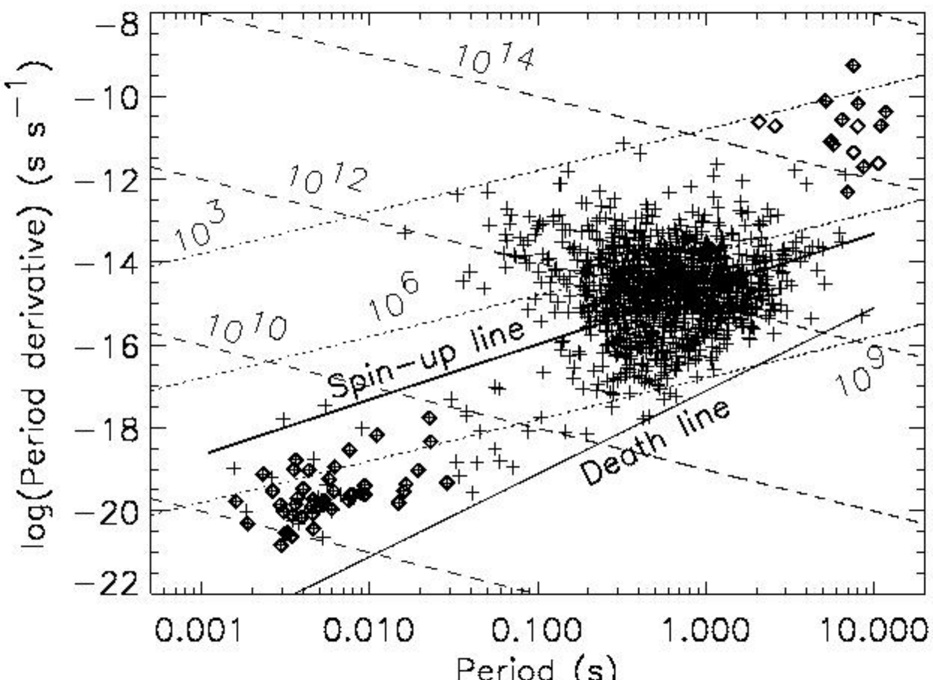
Discoveries of Pulsars

- **In 1967, pulsars were discovered (Hewish, Bell, et al. 1968, Nature)**
- **In1982, the first millisecond pulsar (MSP) was discovered (Backer et al. 1982, Nature)**
- **It was soon pointed out that MSPs should be formed through mass accretion from companions (Alpar et al. 1982, Nature; Radhakrishnan & Srinivasan 1982, Current Science): they are the results of evolution of neutron star low-mass X-ray binaries (LMXBs)**
- **In 1998, the first accreting millisecond X-ray pulsar (AMXP) in a LMXB was discovered (Wijnands & van der Klis 1998, Nature)**

Pulsar Evolution

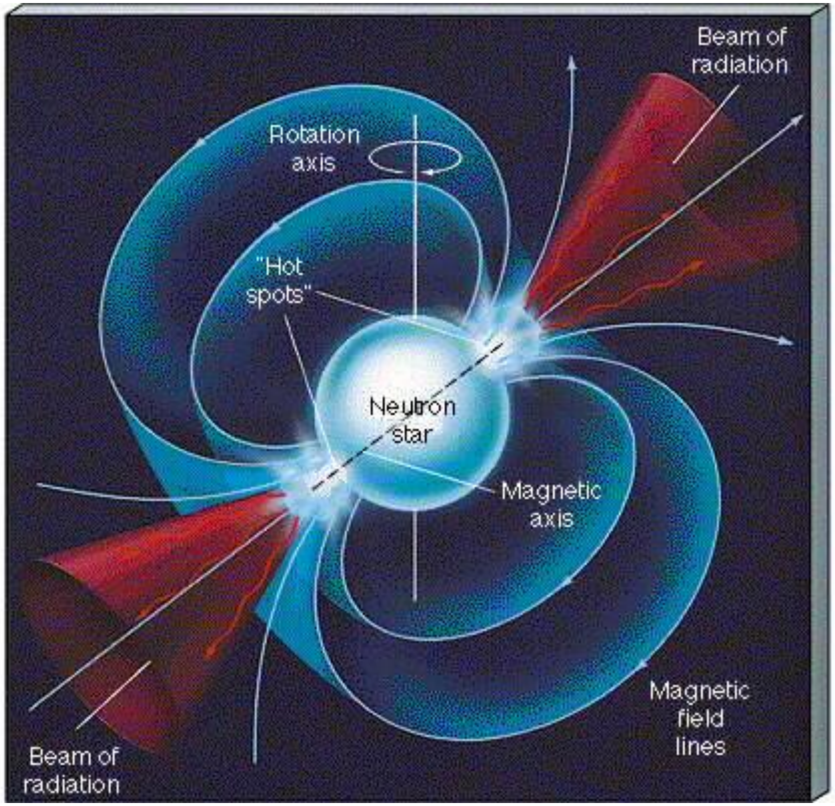






- Neutron stars in the X-ray binary evolution phase can gain sufficient angular momentum and rotation is spun up to millisecond periods: accretion-powered MSPs
- At some point, mass transfer in such a LMXB stops, and the neutron star can re-appear as a so-called black widow pulsar

Neutron Star's Accretion



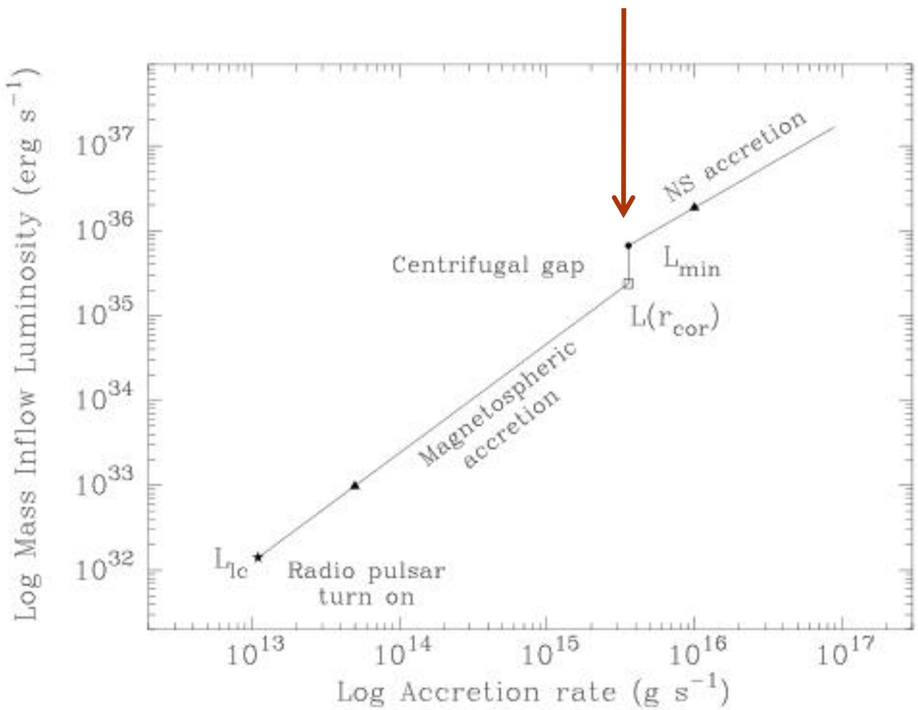
- Light cylinder radius: Rlc=cP/2π;

  if P=2 ms, Rlc~10^7 cm
- Co-rotation radius: Rco^3=GMP^2/4π^2;

  if P=2 ms, M=1.4Msun, Rco~2.6x10^6 cm
- Magnetospheric radius: Rm~Mdot^(-2/7)B^(4/7);

  if Mdot=10^16 g/s & B=10^8 G, Rm~2.8x10^6 cm

Neutron Star's Accretion

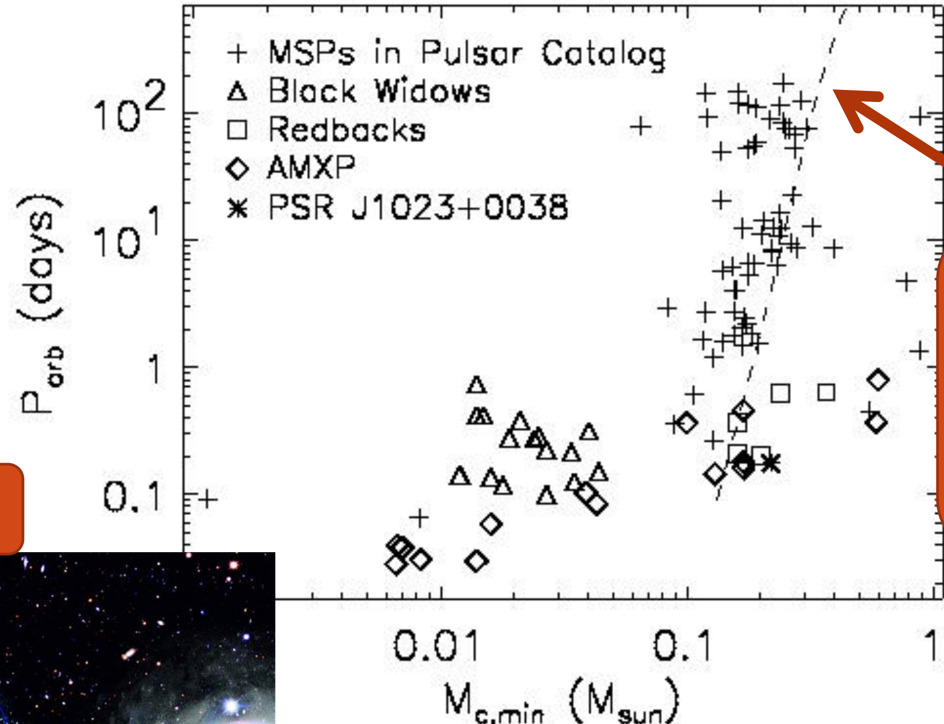


Campana et al. (1998, A&ARv)

1. Rm is the inner radius of a disk
2. Rm < Rco, inflow material is faster than the star's spin and can reach the surface of the star
3. Rm > Rco, "**propeller phase**", inflow reaches Rm, but not to the star
4. Rm > Rlc, no more interaction with the magnetosphere => the **pulsar turns on**;

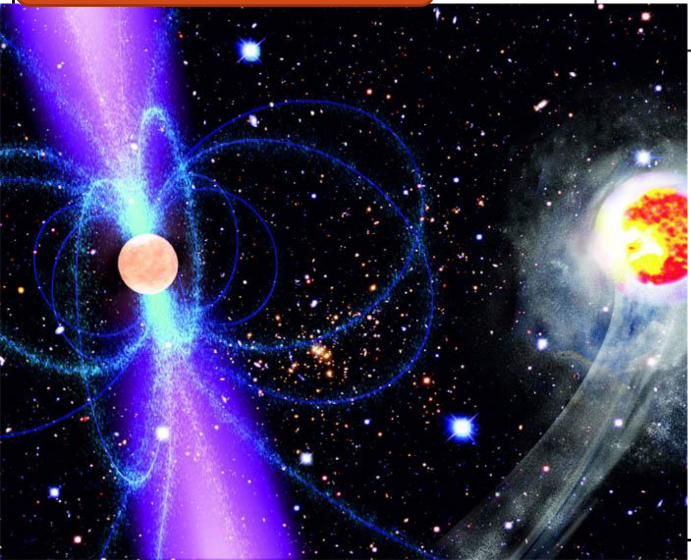
due to the strong radiation pressure, the disk will be disrupted

Different types of MSP binaries



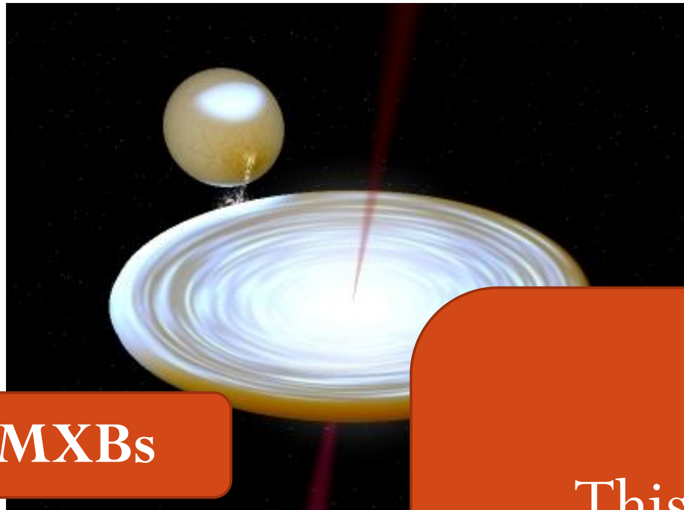
Theoretical prediction for wide orbital systems: Mc~P^(1/4.7)+const (Tauris & Savonije 1999)

Black widow pulsars



•Black widows and redbacks are both eclipsing systems, i.e., radio pulsed emission is eclipsed during certain orbital phase ranges

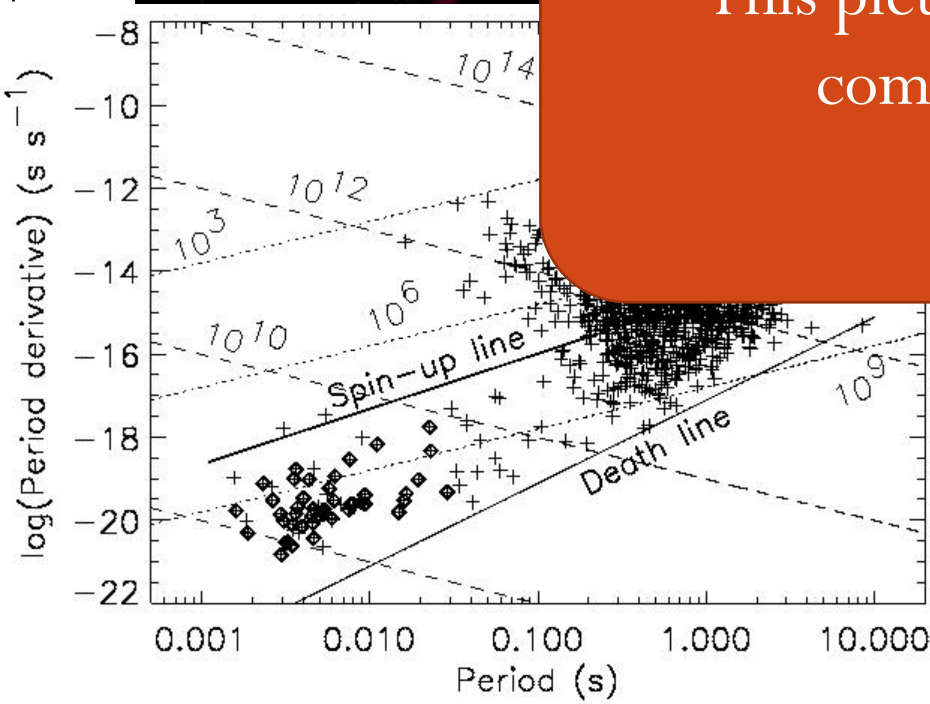
Pulsar Evolution



LMXBs

MSPs

This picture seems complete?



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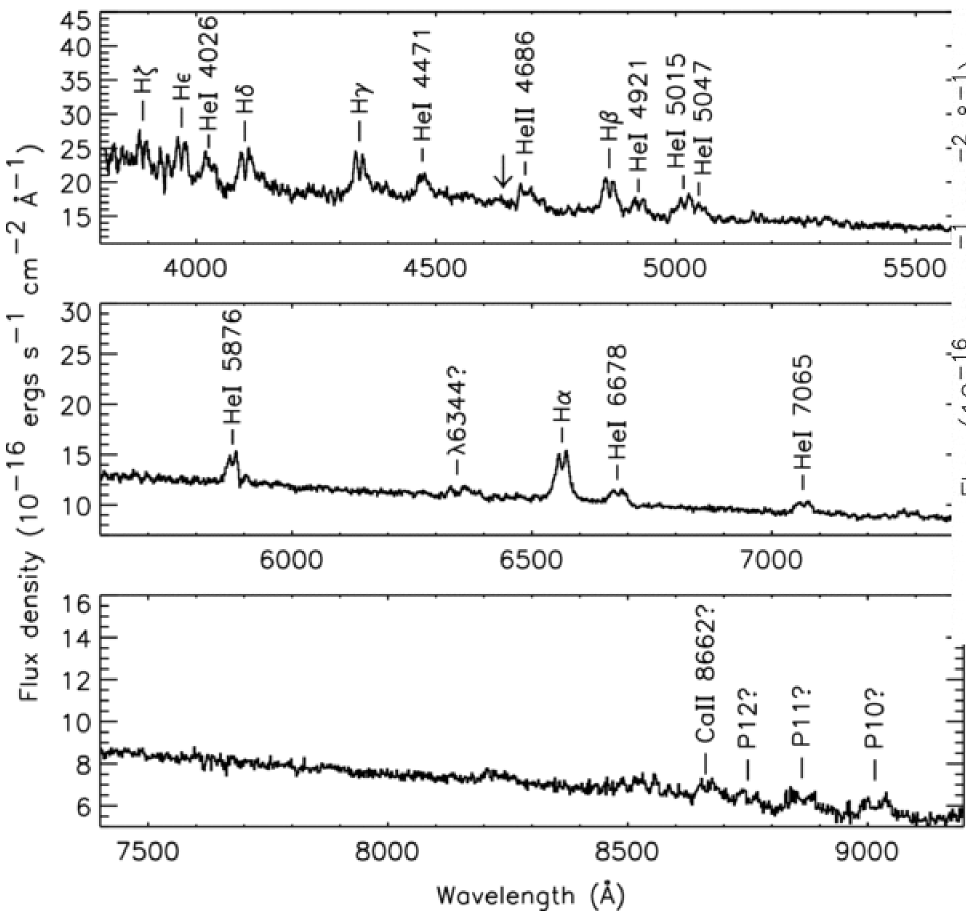
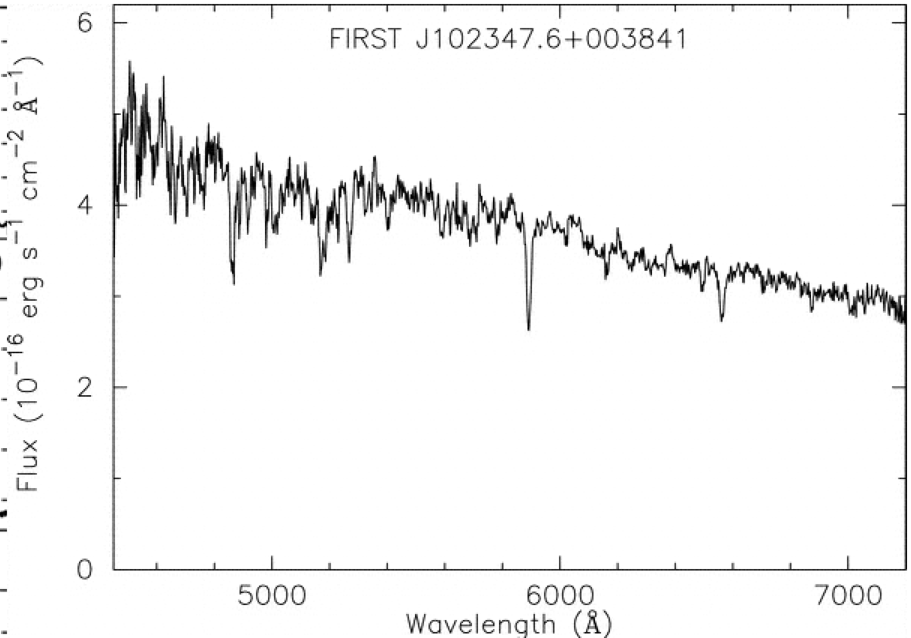
Discovery of the Transitional Pulsar Binary J1023+0038

- Gb=46 deg, V=17.5, bright enough to have been detected by a few sky surveys
- Also detected by the FIRST (radio) survey, attention to the source was first drawn by Bond et al. (2002), and they suggested it's a CV
- However, drastically different spectra were seen after 2002 May; from light curve analysis a neutron star primary was more likely (Thorstensen & Armstrong 2005)
- An MSP, P=1.69 ms, was discovered in an untargeted pulsar survey (Archibald et al. 2009 Science)
- The first system found at the end of its way from a LMXB to a MSP binary(?)

Optical Spectrum Comparison

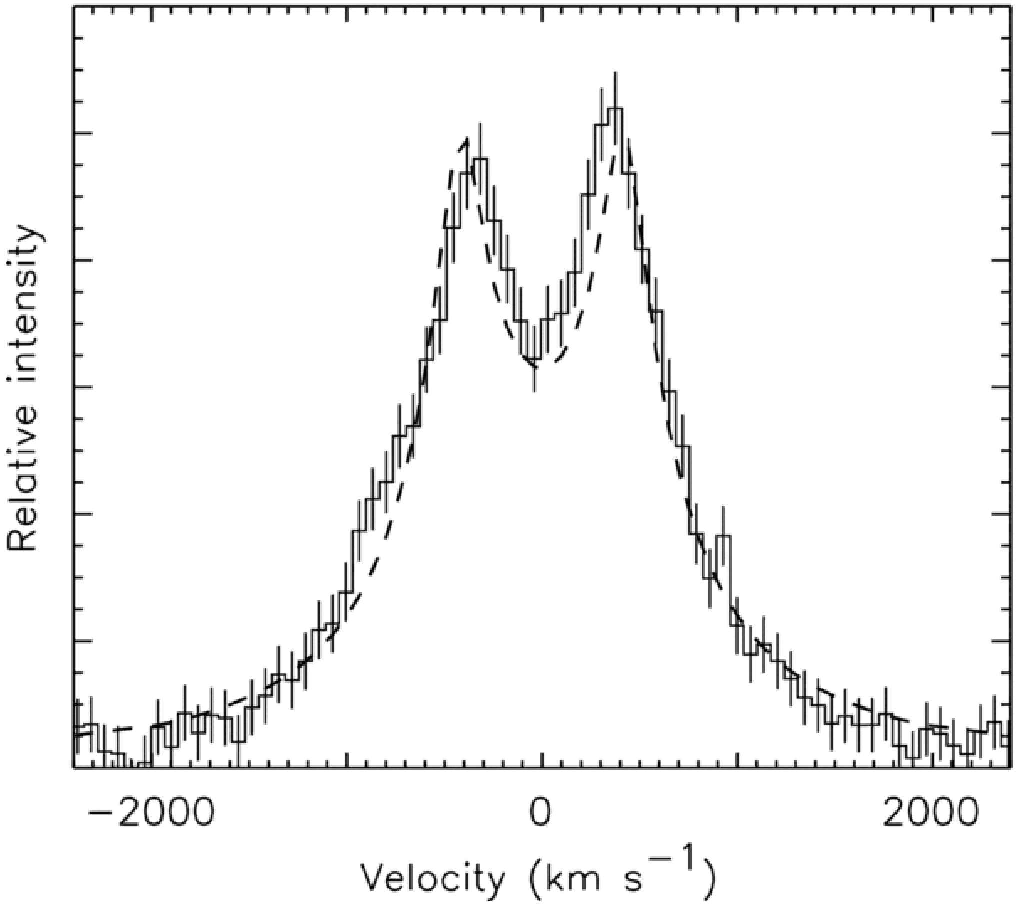


SDSS Spectrum (obtained on 2001 Feb. 1; Wang et al. 2009)



Averaged spectrum after 2002 May (Thorstensen & Armstrong 2005)

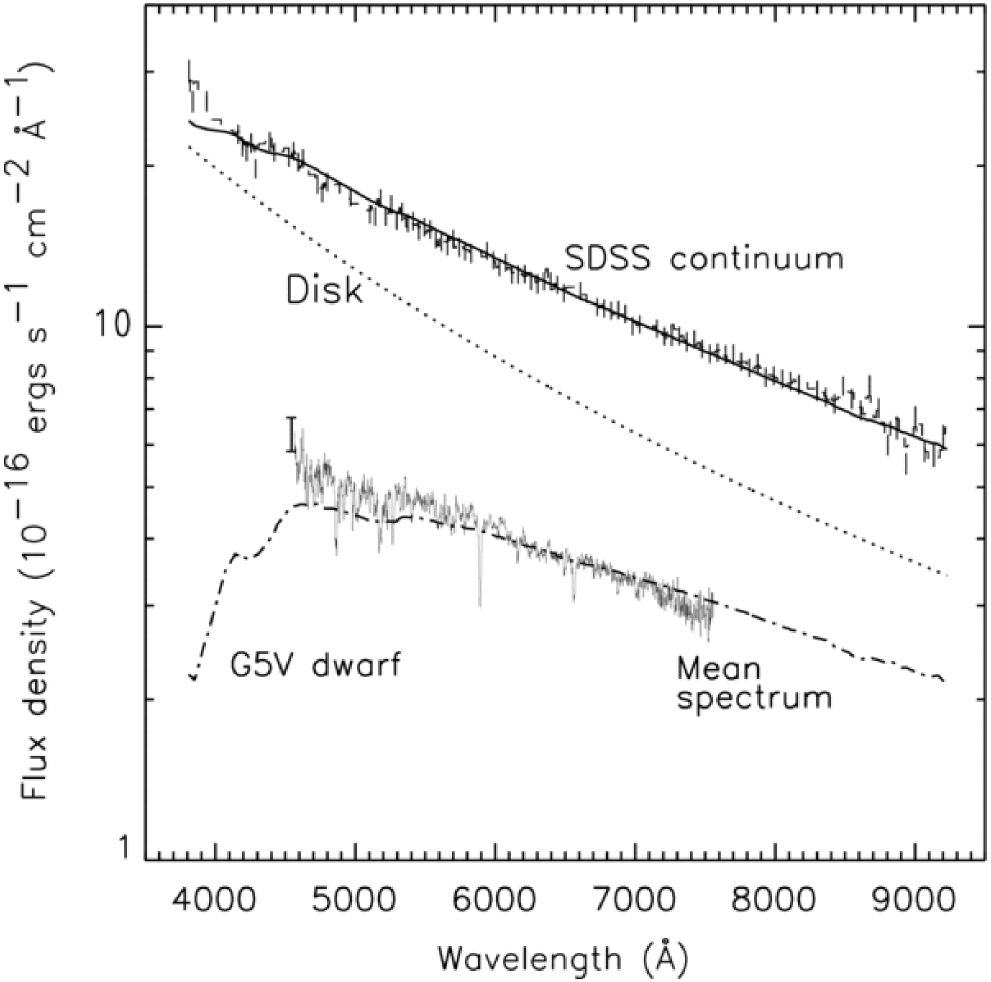
Analysis of the SDSS Spectrum



Hα emission line in the SDSS spectrum

- Double peaked, and can be described by an accretion disk emission model

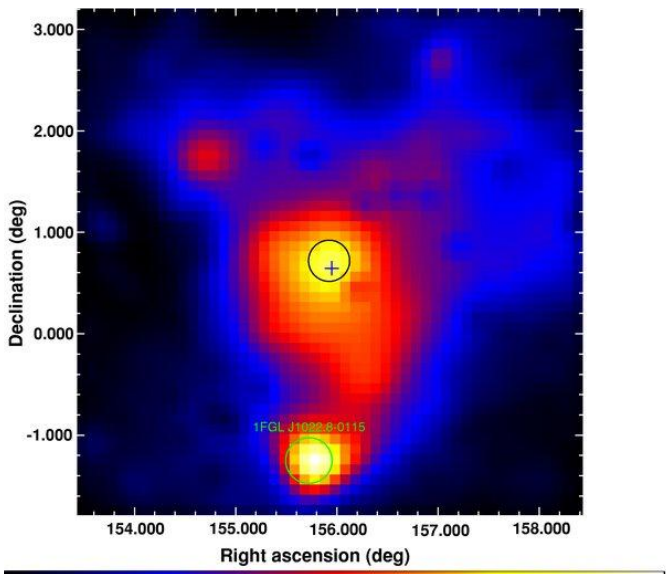
Analysis of the SDSS Spectrum

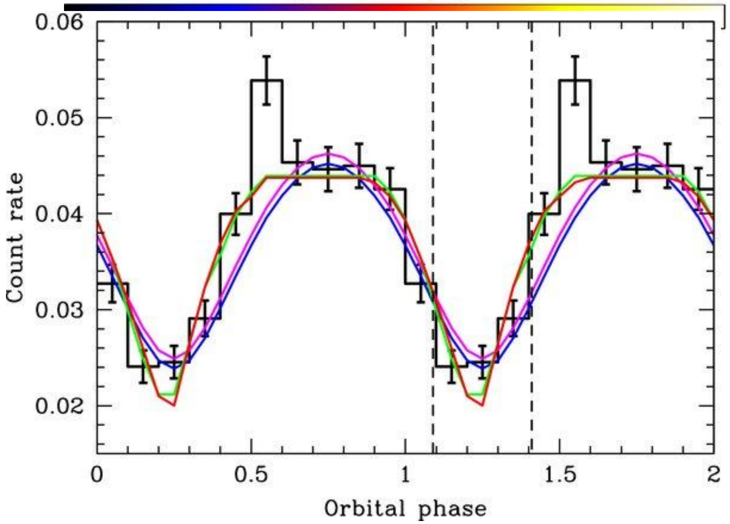


Fitting of the continuum with an accretion disk model

- Mdot ~ 10^16 g/s at the time in the disk
- Not clear if accretion to the neutron star occurred
- Mdisk ~ 10^23 g

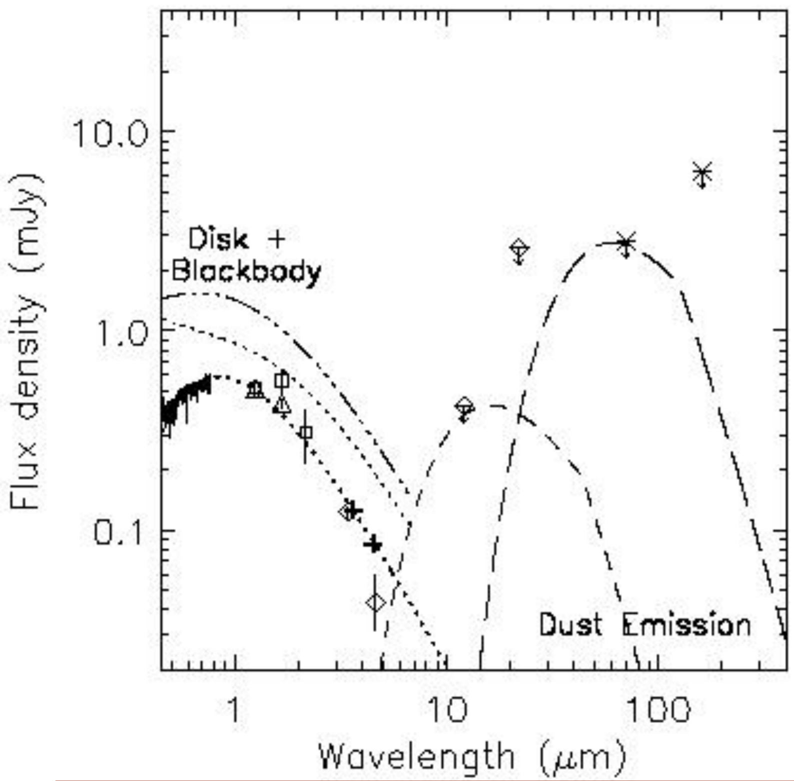
Gamma-ray and X-ray emission





- Has γ-ray emission, detected by Fermi (Tam et al. 2010)
- Orbital X-ray flux variations were detected, indicating X-rays produced from the intrabinary shock (Bogdanov et al. 2011)
- Distance was obtained from VLBI observations => Mass=1.7+/-0.2 Msun

IR Observations

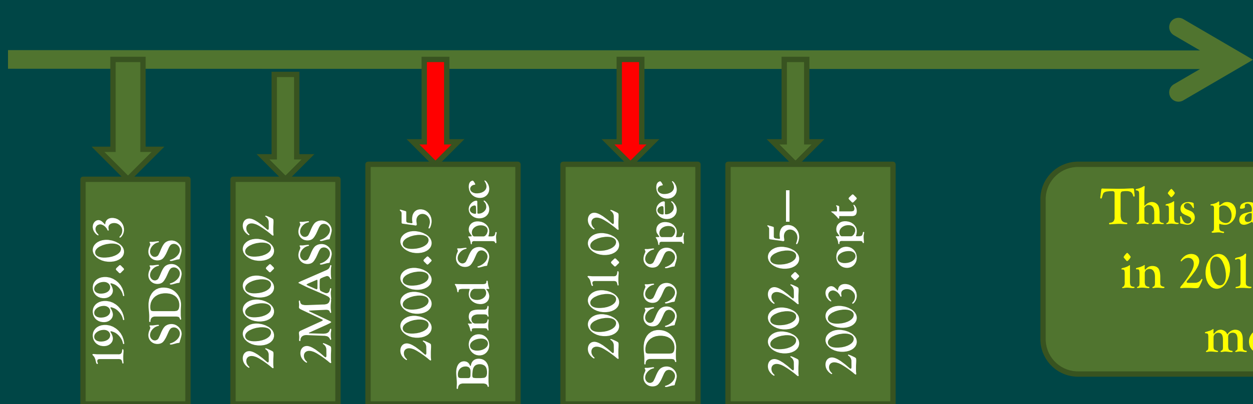


NIR: our ground-based and 2MASS
MIR: *Spitzer and WISE*
FIR: *Herschel*
(Wang X., Wang Z., & Morrell 2013)

- Spitzer MIR and Herschel FIR observations were carried out to search for the remnant of the previous accretion disk
- Comparing our NIR measurements with 2MASS, the disk did not exist on **2000 Feb. 6,** when 2MASS images of the source were obtained.

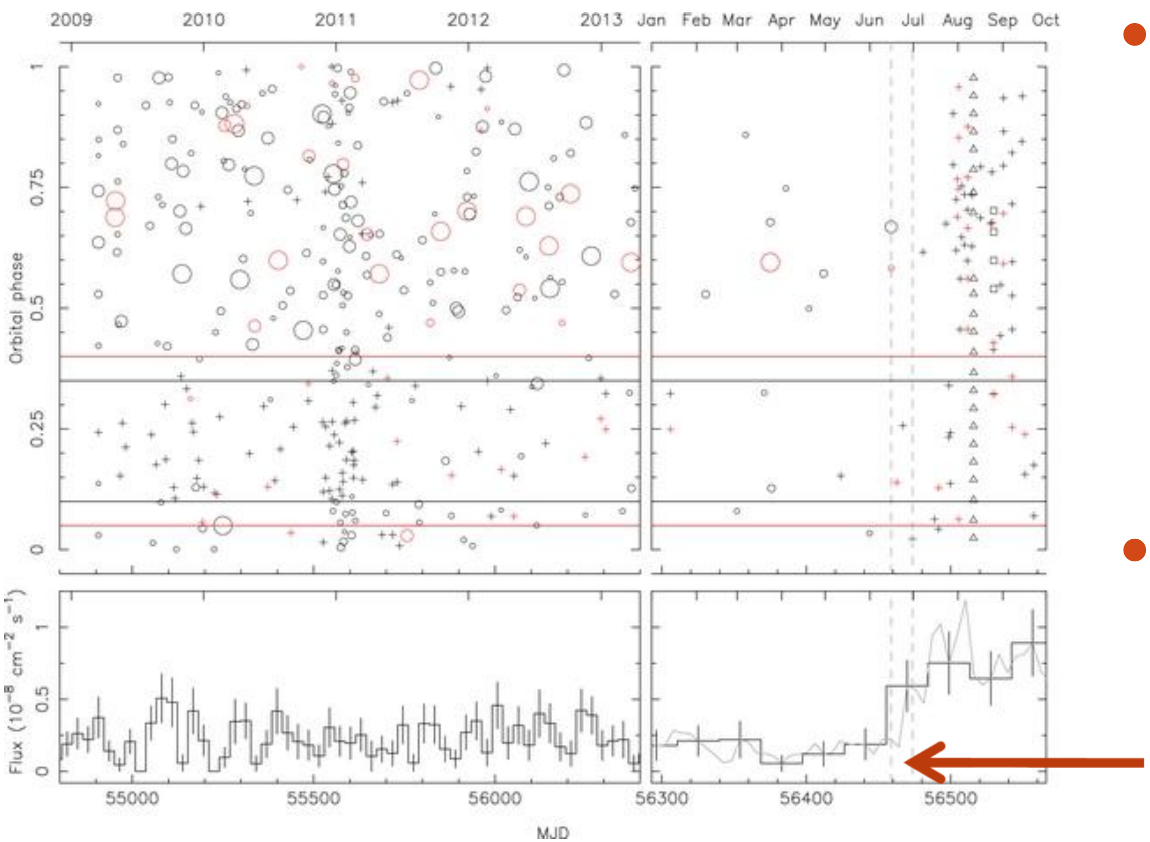
Accretion Disk in 2000-2001

- The disk existed after 2000 Feb. before 2002 May, at most 2.5 yrs
- From RXTE/ASM flux upper limits, it is likely that no accretion to the pulsar occurred during the time
- Since the relaxation time for the companion is much longer than 10 yrs since the interacting activity of the binary, the mass transfer and disk formation may occur again, providing a good source for studying the disk evolution and its interaction with the pulsar wind, and disk disruption processes by the pulsar wind and Gamma-rays emitted from the pulsar



This page was made in 2012 Nov. for a meeting!!!

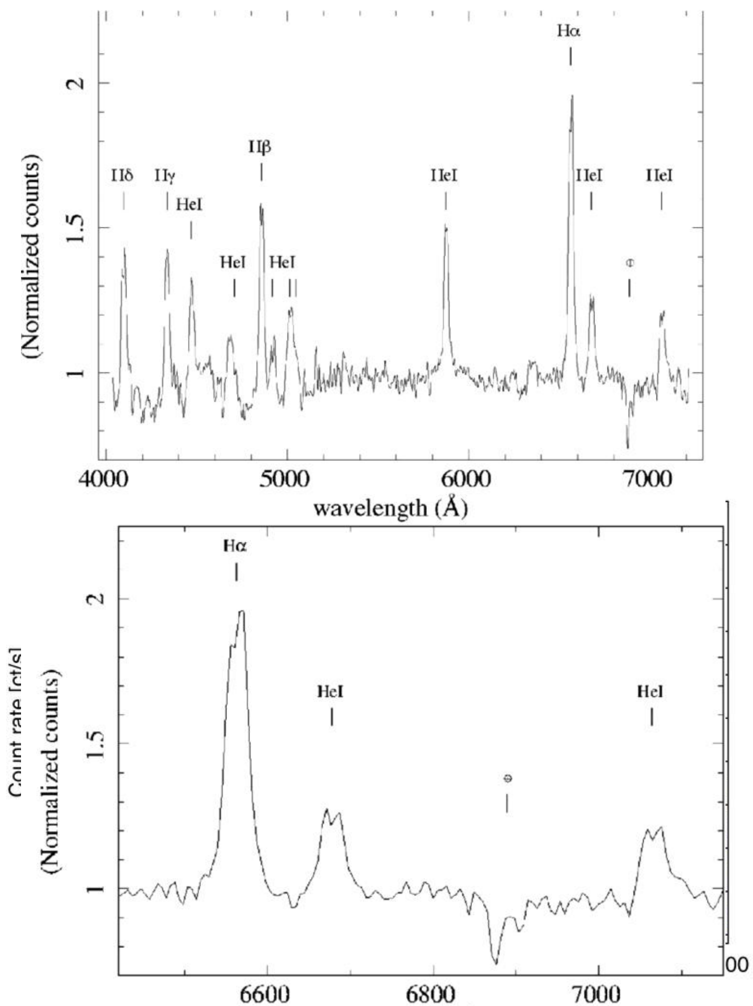
Have a disk again since 2013 June



Radio and gamma-ray monitoring of PSR J1023+0038 (Stappers et al. 2014)

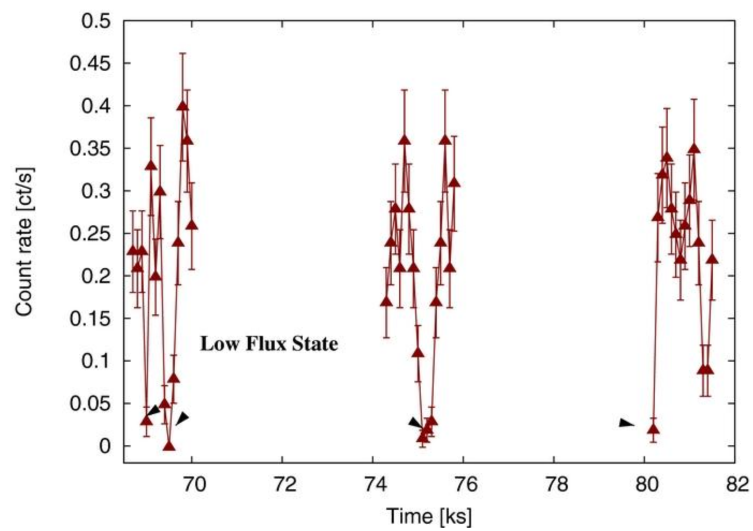
- Around superior conjunction (when the pulsar is behind the companion), radio pulsed emission is eclipsed
- A state transition occurred around June 15-30, 2013, as the pulsar can not be detected since then

Optical and X-ray



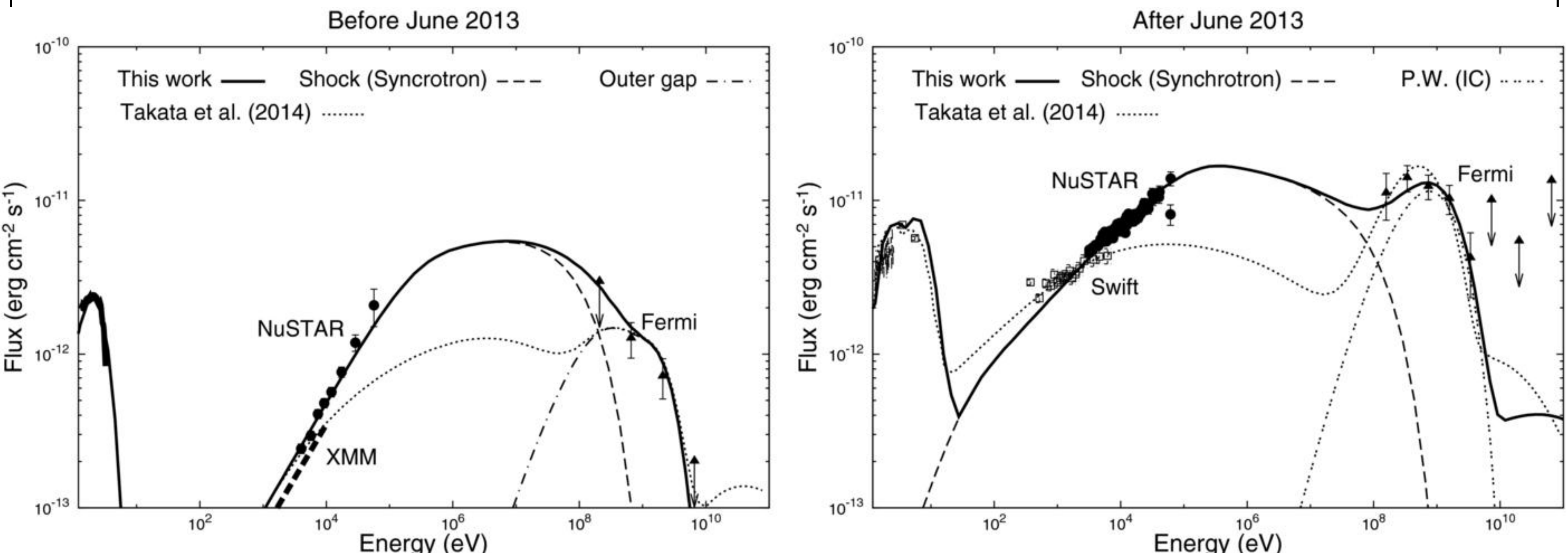
F. Coti Zelati et al. MNRAS 2014

- The binary is back to having an accretion disk, revealed by optical spectroscopy
- X-ray show large (100 times) fast (in 10 sec) flux variability



Patruno et al. 2014

Broadband spectrum during the high state

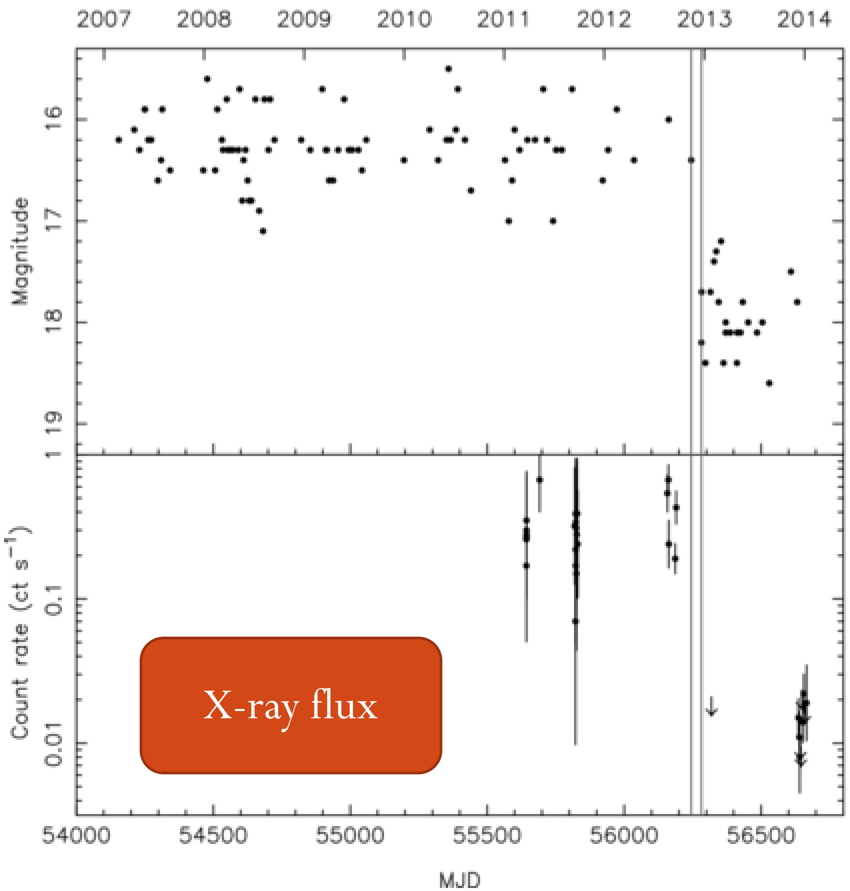


Li et al. 2014, ApJ

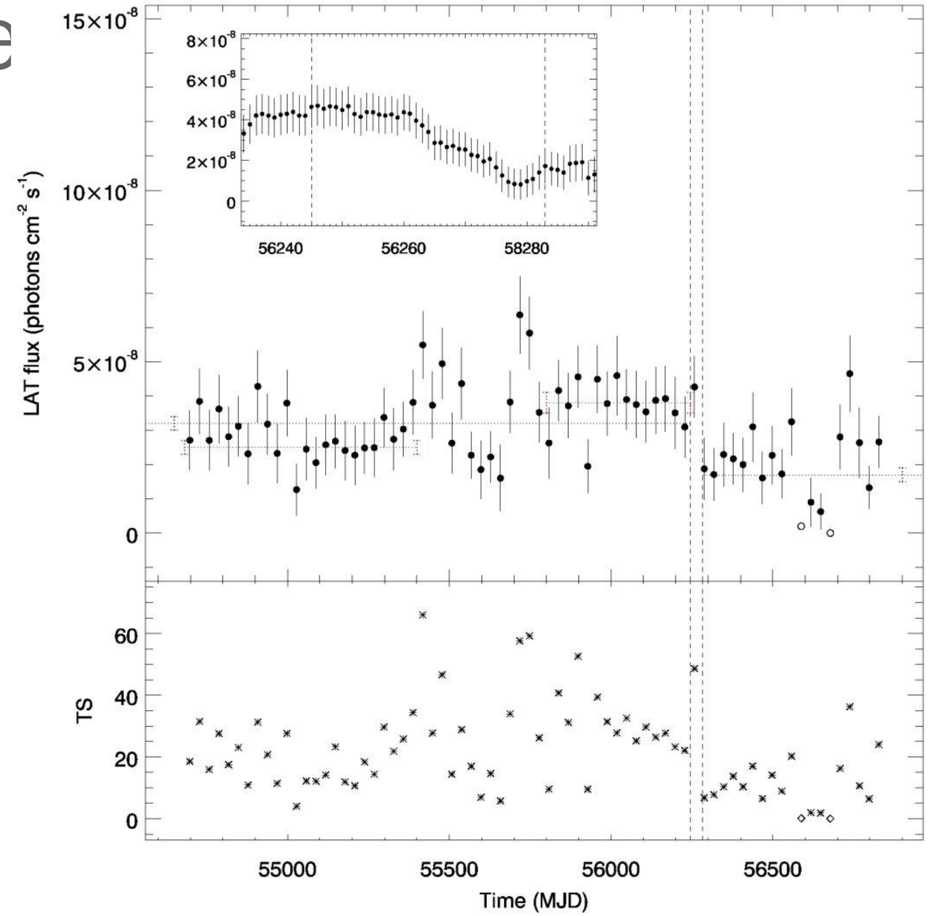
- No disk, only see the companion in optical
- Lots of material in the binary, as radio emission is eclipsed during certain phase ranges
- Power-law X-rays, orbitally modulated
- Has gamma-rays, likely from the pulsar

- Has an accretion disk, double peaked emission lines
- The pulsar is not detectable at radio
- Power-law X-rays, but not modulated
- Stronger gamma-rays

2nd Transitional Source XSS 12270-4859

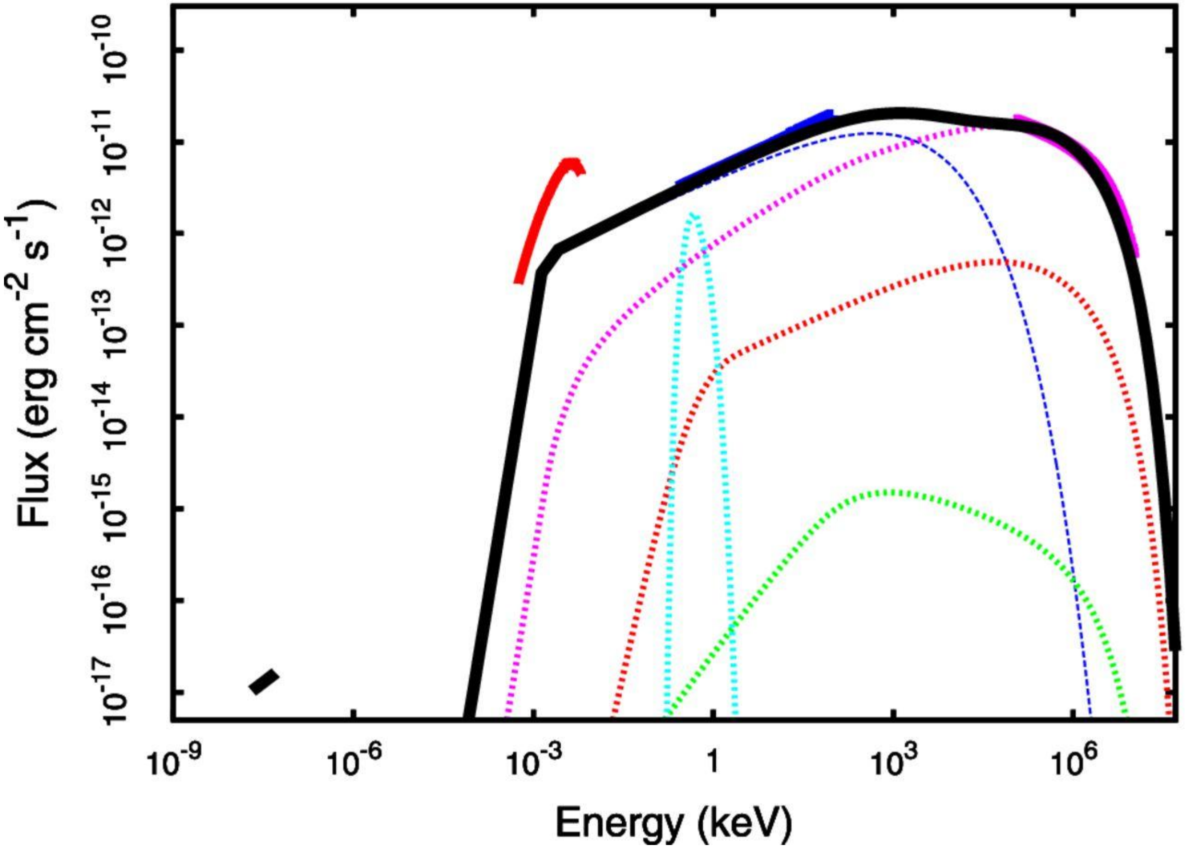


Disk disappearance occurred at the end of 2012 (Bassa et al. 2014)



- Basically the same as PSR J1023+0038
- After the transition:
  - a P=1.69 ms pulsar is seen
  - X-rays are orbitally modulated
  - Gamma-ray flux has decreased by a factor of 2

Alternative Propeller Model for the Accretion State



Papitto, Torres, & Li (2014)

- The source is at a propeller phase
- Relativistic electrons are accelerated by shocks at the magnetospheric interface
- Blue: synchrotron
- Magenta: self-synchrotron Compton scattering
- Red: inverse Compton scattering

Intrabinary Emission From Eclipsing Systems

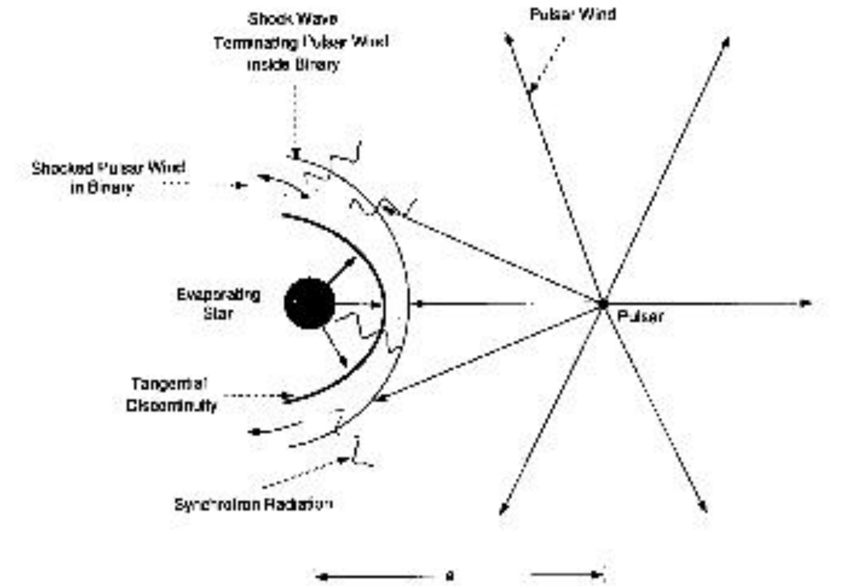
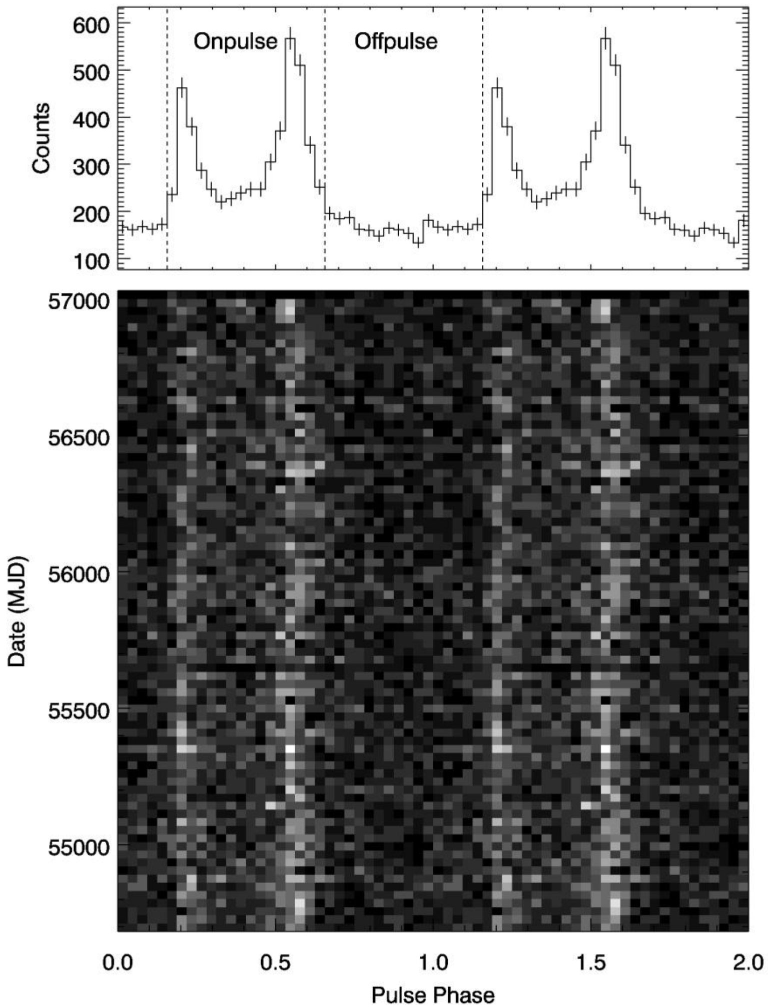


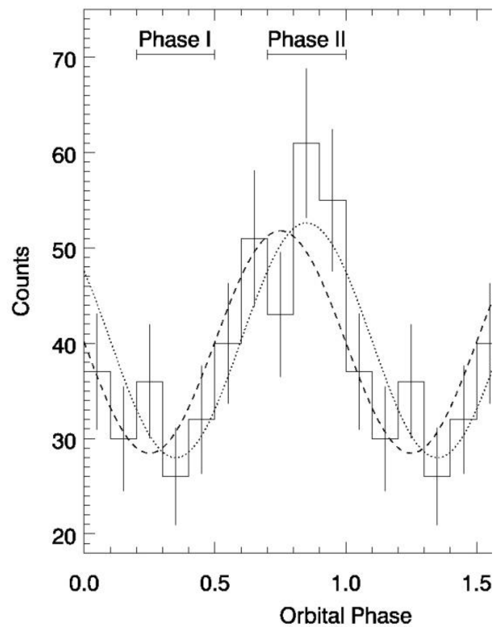
FIG. 2 Schematic representation of the shock geometry near the companion star.

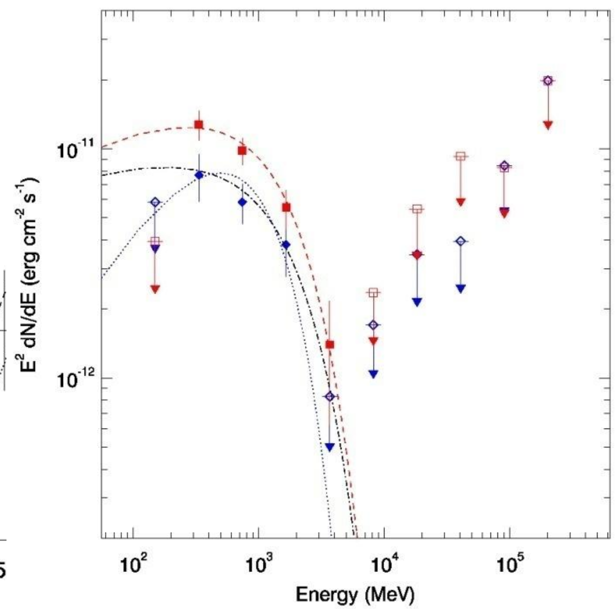
Picture proposed by Arons & Tavani (1993)

- Because of the discovery of the first black widow system, it has long been proposed
- Eclipsing implies the presence of lots of material produced by ejection from the companion
- Intrabinary shocks exist and the accelerated particles can have high-energy emission
- X-ray observations of black widows and redbacks have confirmed this picture

Recently Discovered PSR J1311-3430



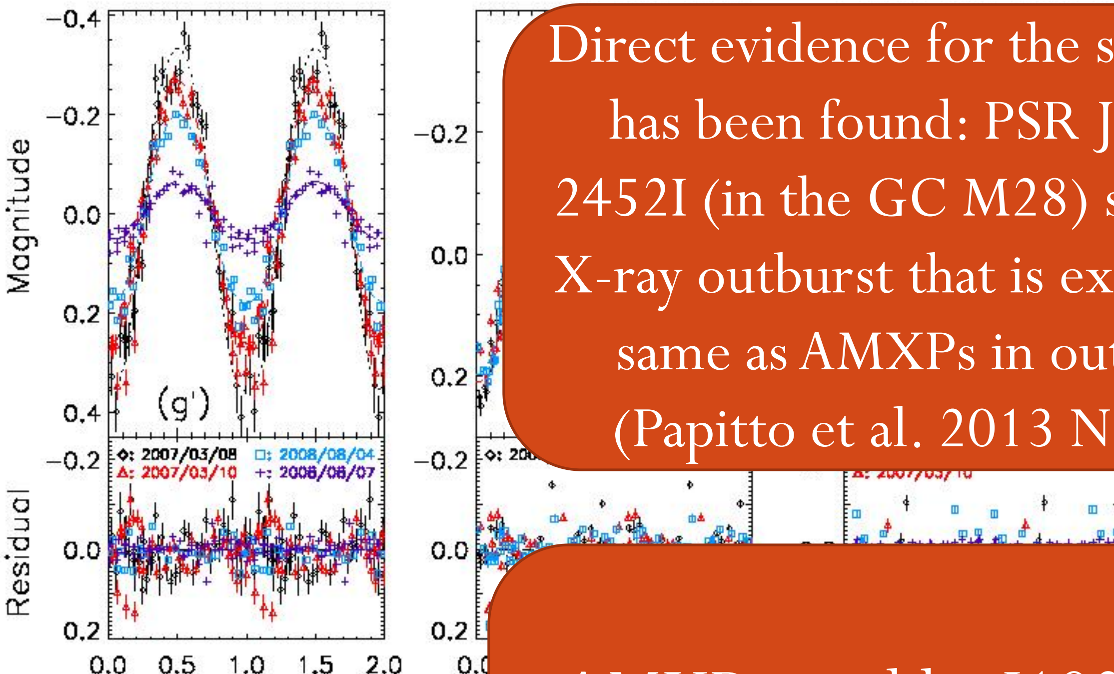


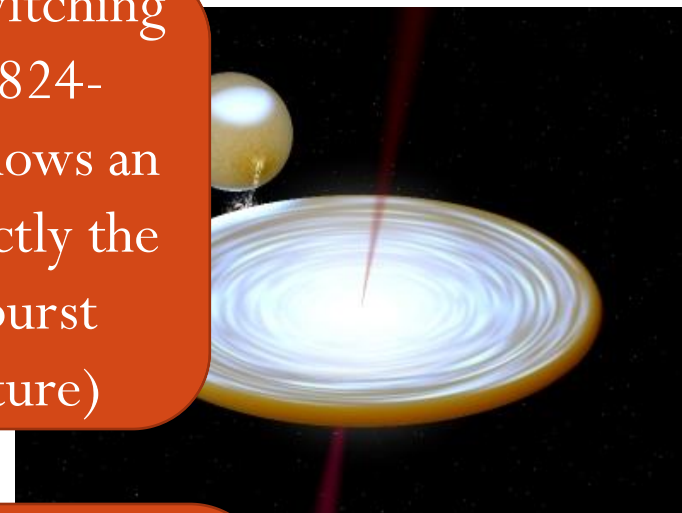


Xing & Wang (2015, submitted to ApJL)

- The only MSP found from Fermi Gamma-ray timing（Pletsch et al. 2012, Science)
- Orbital period 94 min， companion mass 0.01Msun
- In off-pulse data, orbital modulation is found
- Provide clear evidence for intrabinary gamma-ray emission

Accreting Millisecond X-Ray Pulsar Binaries in Quiescence





Direct evidence for the switching has been found: PSR J1824-2452I (in the GC M28) shows an X-ray outburst that is exactly the same as AMXPs in outburst (Papitto et al. 2013 Nature)

J1808.4-3658

AMXPs are like J1023+0038 when the latter has an accretion disk

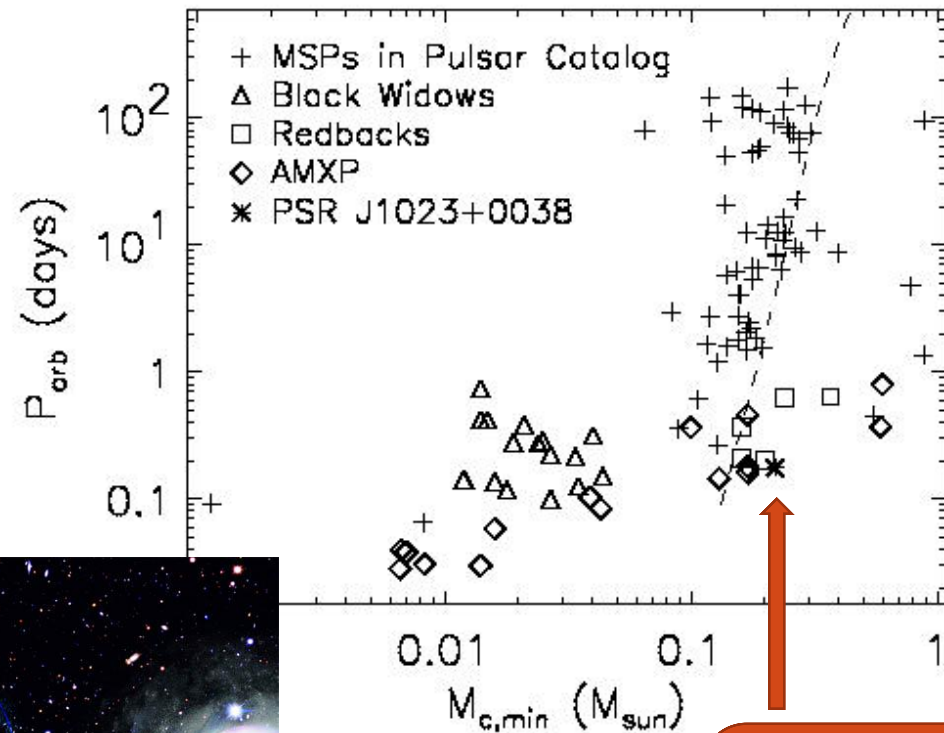
- Optical modulat … anion is strongly irradiated, Lir~ …
- X-ray luminosity … itude lower than required
- Solution: the primary switches to be a regular radio pulsar, with its spin-down energy as the irradiation energy source (suggested by Burderi et al. 2003)

Property Comparison

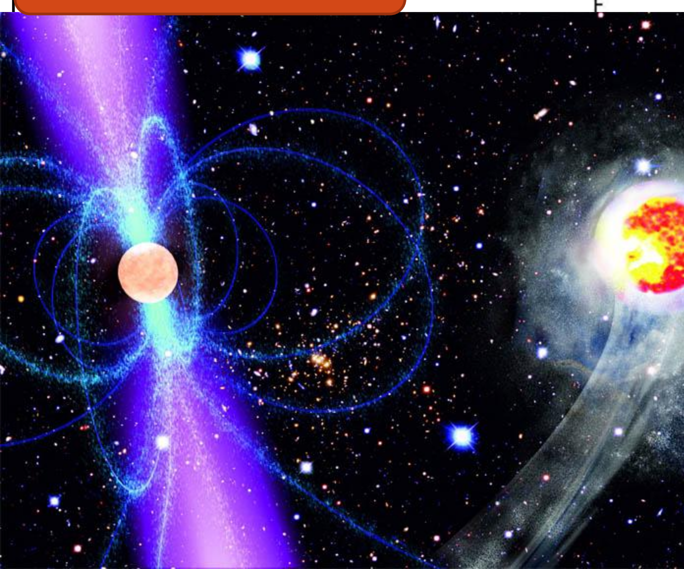
- Transitional MSP binaries
  - High state: **have an accretion disk, higher X-ray and gamma-ray flux, no radio pulsed emission**
  - Low state: no disk, low orbitally modulated X-rays, low gamma-rays (likely from the pulsar), pulsed radio emission

- AMXPs
  - Outburst: 10^36 erg/s X-ray emission, pulsed X-rays, brighter optical emission
  - Quiescence: **10^32 erg/s X-ray emission, no pulsations seen, faint but strongly modulated optical emission (the disk still exists)**

Different types of MSP binaries



Black widow

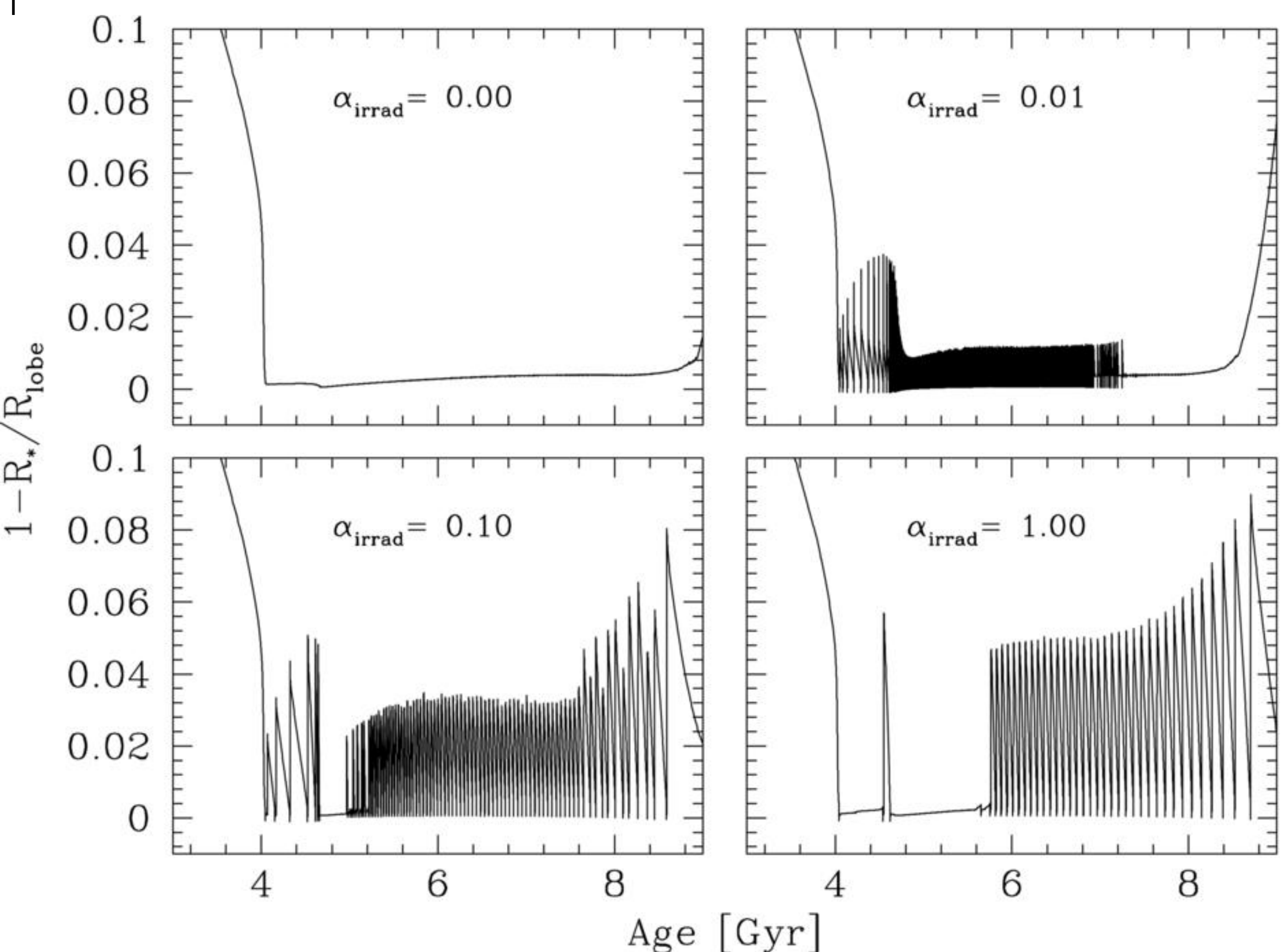


PSR J1023+0038
and other redbacks

Further Speculation

- Roughly 200 LMXBs are identified, most of them are relatively bright or once were bright (~10^36 erg/s)
- There should be more out there, but not identified
- Indeed, there is a group so-called Very Faint X-ray Binaries (VFXBs; e.g., Heinke et al. 2014), with quiescenct Lx~10^33 erg/s
- The point is these VFXBs could be considered as the transitional systems too if the neutron stars do not accrete and thus turn to be regular radio pulsars
- Question: how to prove this?

Other Scenario



- Irradiation plays an important role in LMXB evolution
- Depending on it, the companion may swing between filling the Roche lobe and being slightly smaller (quasi—Roche-lobe overflow; Benvenuto et al. 2015)
- However, the time scale for the swing is long, and we should not see it; comparing to what we see in J1023+0038 (10 yrs time scale or shorter)

Summary

- A new type of phenomenon in MSP binaries is found: the systems can switch between the states of **having an accretion disk and being disk-free in a short time scale of 10 years**
- They are likely at the transition phase from LMXBs to MSP binaries, during which interesting multi-wavelength properties are displayed
- Other possibility is they could be at the state of **quasi Roche lobe overflow**, due to irradiation of the companion by the neutron star primary in such a binary
- In either case, many such systems might exist and wait to be found

Thank you for your attention!