Substellar Companions around Neutron Stars

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Abstract: Planets or substellar companions around neutron stars can give valuable insights into the neutron star's formation history considering e.g. birth kicks or fallback disks. They may also help to derive neutron star masses which would be very welcome, especially if the radius can be derived by other means as for the radio-quiet X-ray thermal neutron stars. Currently there are two planetary systems around ms- pulsars known. Some of the formation theories can already be ruled out for these systems. However, statistics is very poor and other search techniques are needed to cover also young, even radio-quiet neutron stars. Among the objects we study is the famous RX J1856.5-3754 for which a substellar object could help to constrain the equation of state as the radius has be already derived by its X-ray thermal emission.

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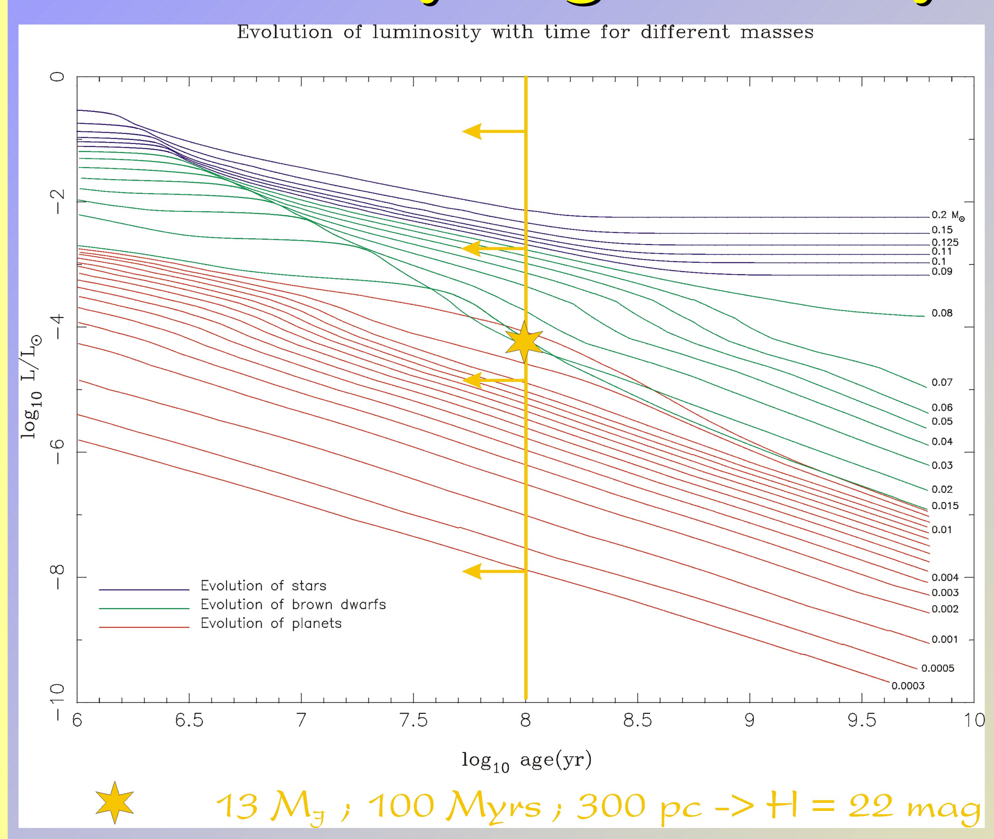
Why search for neutron star planets ?

- study of different planet formation mechanisms
- planet investigation has advantage of good contrast planet – host star
- get clues on supernova and neutron star physics
- get lower limit on planet formation rate around massive stars

Direct Imaging of young and nearby neutron stars



for young neutron stars:

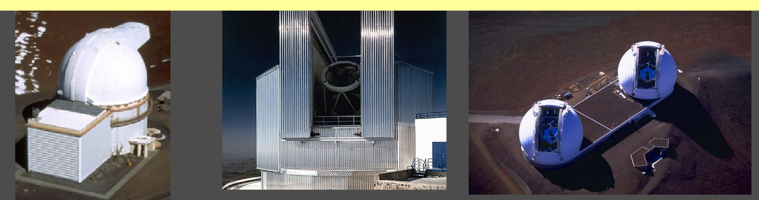
- progenitor lifetime negligible
- possible substellar companions also young
- substellar companions warm enough to be seen at infrared wavelengths
- neutron stars faint in IR
- nearby neutron stars have large proper motions

up to distances of 300pc we can detect a 13 $M_{Jupiter}$ planet around a neutron star younger than 100 Myrs

Status of the project

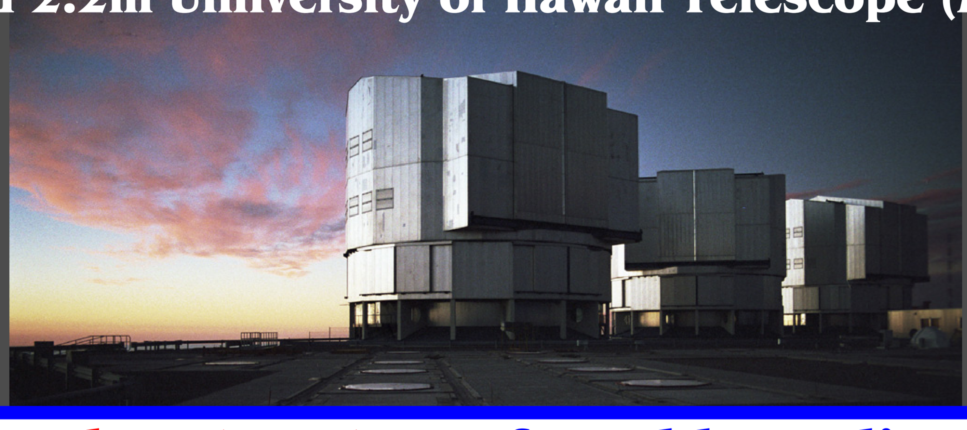
- First epoch for 12 out of 14 neutron stars observed
- Many objects excluded by their NIR /optical color
- Several companion candidates

- Second epoch for RXJ1856.6-3754 and PSR 1932+1059
- no co-moving objects down to 10.6 M_{Jup} and 52 M_{Jup}
- next second epoch observations scheduled 2006/07



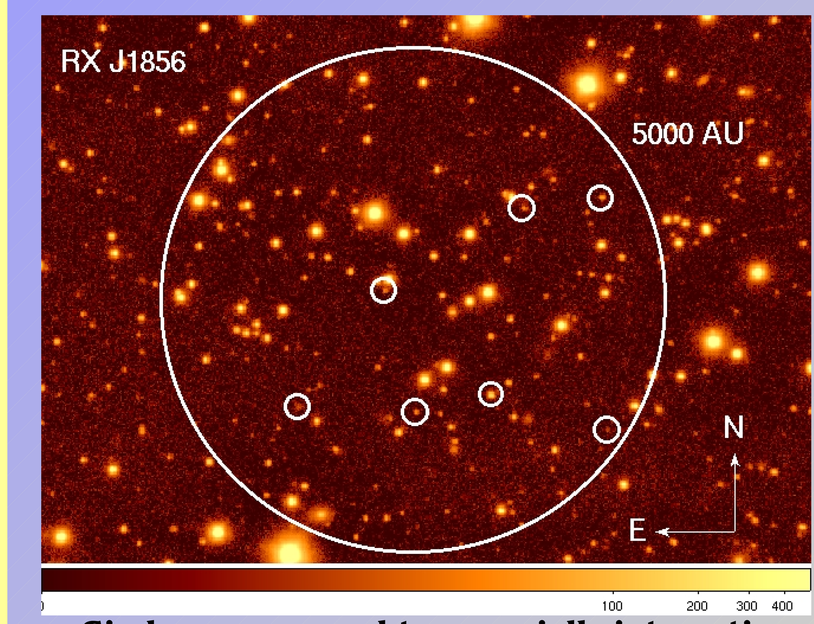
➔ 14 young (< 100 Myr) and nearby (<300 pc) neutron stars

➔Observations with VLT ISAAC (*H-band*), NTT SOFI (H-band) , Keck (*K-band*) and 2.2m Uiniversity of Hawaii Telescope (*K-band*)



Substellar companions around RXJ 1856.6-3754 ?

First epoch:	**May 2003**	
VLT ISAAC	*H*-band	
Second epoch: May 2006		
NTT SOFI	*H*-band	

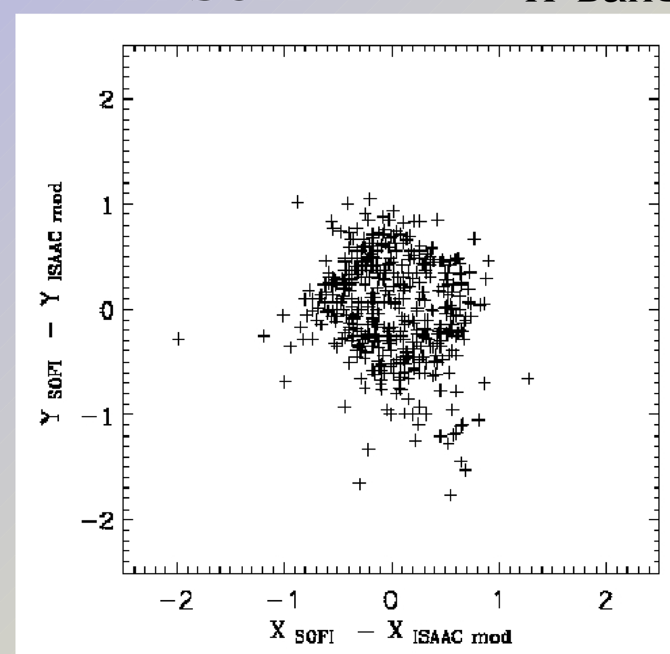


Circles correspond to especially interesting objects, identified by NIR / optical colors

Proper motion: *Walter 2001*
RA.: 326.7 +/- 0.8 mas / yr
DEC.: -59.1 +/- 0.7 mas / yr

Expected shift: 1pixel =143 mas
6.9 pixel in *x* and -1.2 pixel in *y*

Errors (worst case): 4.4 pixel
Gauss fits: 3sigma=1.6 pixel
(for each epoch)
Pixel size adaption: 3sigma=1.2 pixel



Source position shifts in pixels between first and second epoch
after pixel size transformation
(ISAAC: 147 mas -> SOFI: 143 mas)

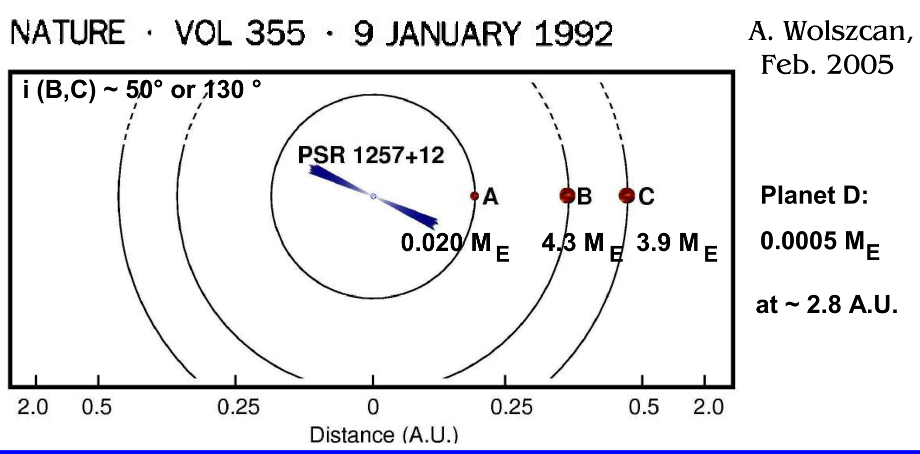
no co-moving object down to *H* = 21.6 mag

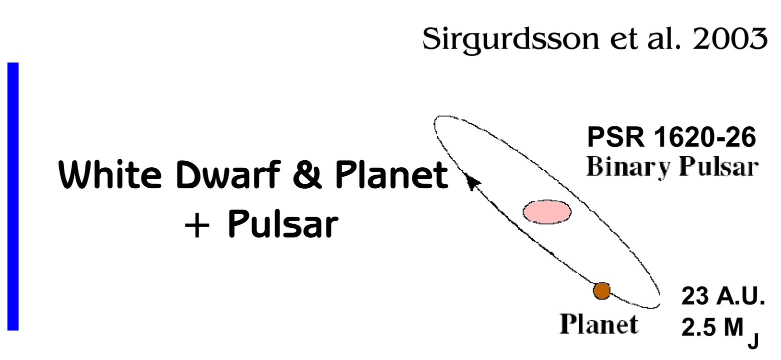
assuming an age of ~1Myr and a distance of 161 pc :

no substellar companions down to 10.5 Jupiter masses

no NIR counterpart for RXJ 1856.6-3754 down to *H* = 22.6 +/- 0.5 mag

Known pulsar planet systems found by radio pulse timing





Observational Techniques to find neutron star planets

Neutron stars are optically very faint (>25 mag), and are best observed at X-ray or radio wavelengths

Direct Imaging:
- reflected optical light very faint (>27 mag)
- young planets can be found in the infrared good contrast !

Transit method:
- neutron star is eclipsed by planet
- active regions on neutron star

Astrometric wobbling:
- best *Chandra* spatial resolution is ~1"

Radial velocity method:
- X-ray spectroscopic resolution is > 600 km/s
- optical ~3 m/s, but neutron star to faint

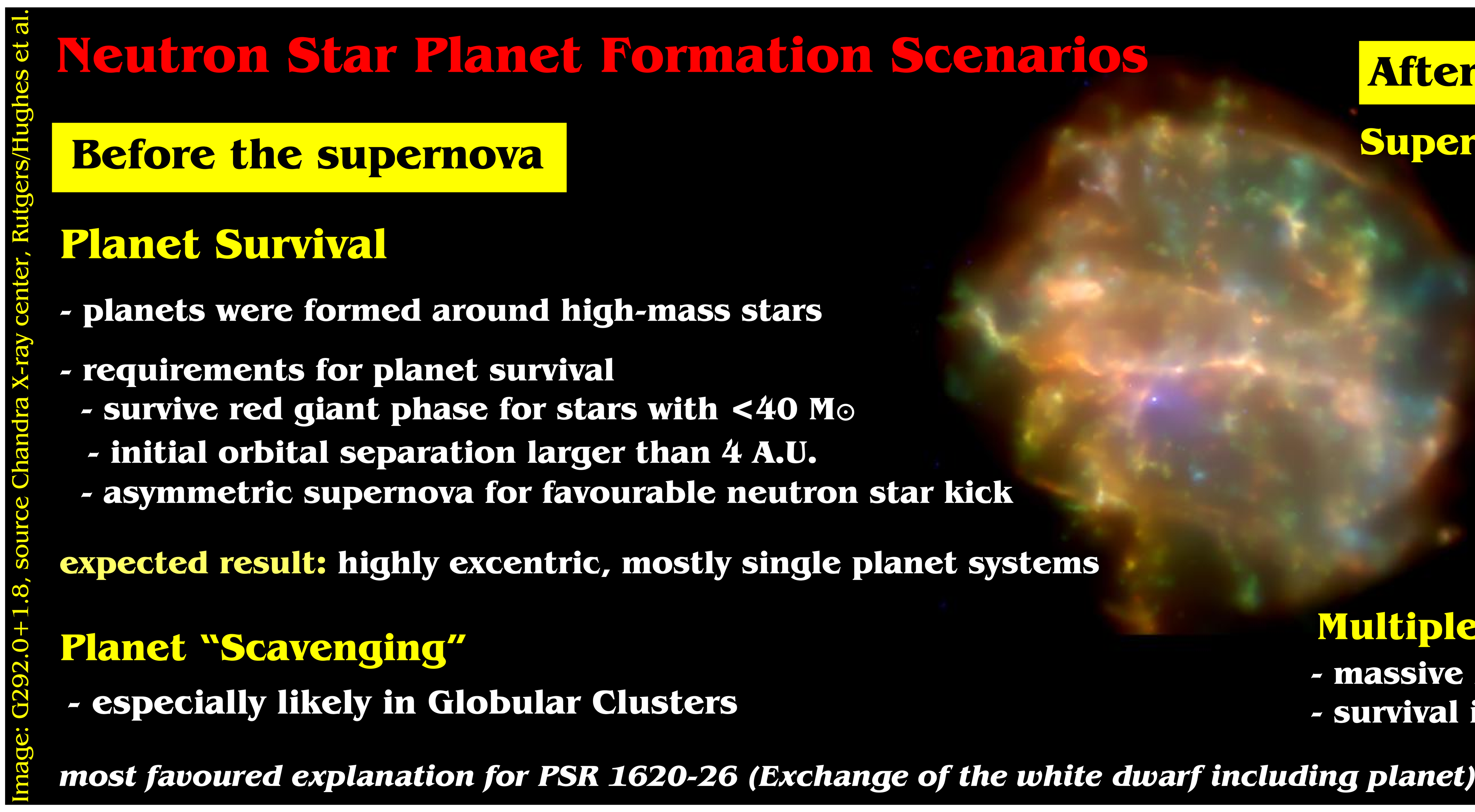
Radio pulse timing technique::

Periodic variations in the observed pulse phase generated by reflex orbital motion of the pulsar due to orbiting planets

+ sensitive to terrestrial planets
- not sensitive to young (timing noise) and radio-quiet neutron stars

Neutron Star Planet Formation Scenarios

Reference: e.g. Podsiadlowski 1995



Before the supernova

Planet Survival

- planets were formed around high-mass stars
- requirements for planet survival
  - survive red giant phase for stars with <40 M⊙
  - initial orbital separation larger than 4 A.U.
  - asymmetric supernova for favourable neutron star kick

expected result: highly excentric, mostly single planet systems

Planet "Scavenging"

- especially likely in Globular Clusters

most favoured explanation for PSR 1620-26 (Exchange of the white dwarf including planet)

After the supernova :

Supernova Fallback
- small fallback mass lower than 0.1 M⊙

Multiple Systems – Disrupted Companion Model
- evaporation of pulsar companion star in binaries
- bound material forms circumbinary disk
- from disk planet formation

possible for PSR 1257+12

Multiple Systems – Circumbinary Disk Model
- dynamical disruption of low mass or degenerate star
- from dense disk planet formation

possible for PSR 1257+12

Multiple Systems – Massive Binaries
- massive binary results in moderate supernova kick
- survival in spiral-in time longer than Thorne-Zytkow-Object lifetime