Have strange quark stars been discovered ?

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Plan

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2. Theoretical models of strange quark stars
3. Recent Chandra observations

1

Strange quark matter

The strange quark

Quark properties

flavor	d	u	s	c	b	t
spin	$1/2$					
baryon number	$1/3$					
electric charge	$-\frac{e}{3}$	$\frac{2e}{3}$	$-\frac{e}{3}$	$\frac{2e}{3}$	$-\frac{e}{3}$	$\frac{2e}{3}$
isospin (z-comp.)	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
mass $[\mathrm{MeV}\,c^{-2}]$	~ 7	~ 3	~ 150	~ 1200	~ 4200	$\sim 175\ \mathrm{GeV}\,c^{-2}$

Recall: nucleons : **p = uud**, **n = udd**

hyperons : Λ **= usd**, Σ^+ **= uus**,...

mesons : π^+ **=** $\mathbf{u\bar{d}}$, π^- **=** $\mathbf{\bar{u}d}$,...

Strange quark matter hypothesis and strange stars

1971: A.R. Bodmer $\rightarrow$ the ground state of nuclear matter may be a state of **deconfined quarks**.

1984: E. Witten reformulated (independently) this idea, and contemplated the possibility that neutron stars are in fact **strange quark stars**.

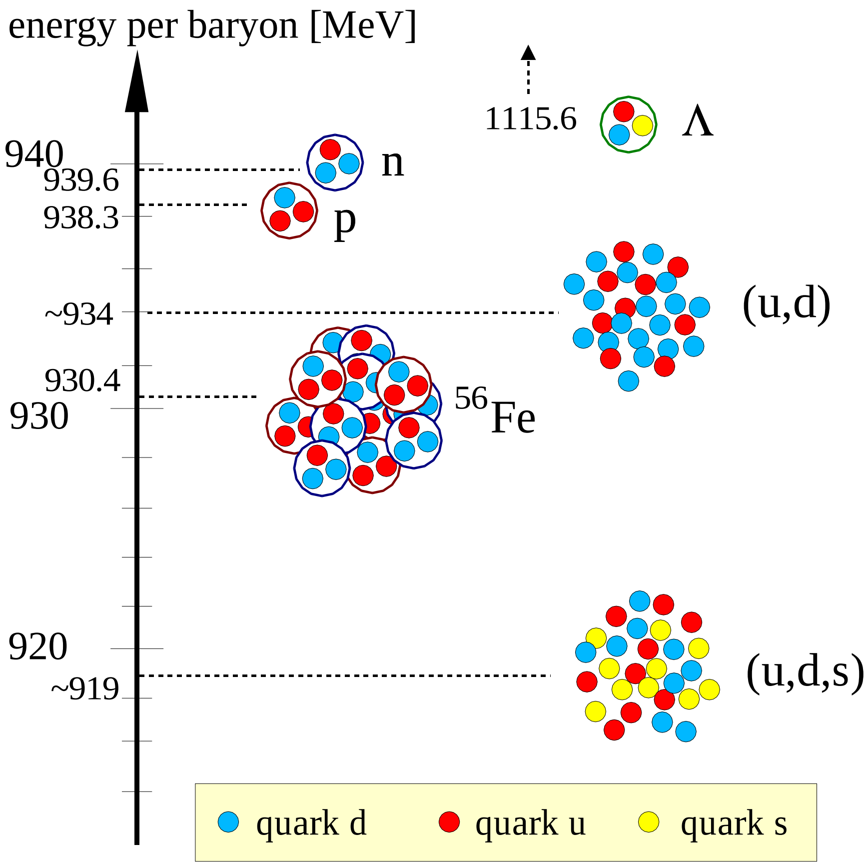
1986: first numerical models of static strange stars by P. Haensel, J.L. Zdunik & R. Schaeffer, as well as C. Alcock, E. Farhi & A.V. Olinto.

1989 : announcement of a half-millisecond pulsar in SN 1987A

1996 : discovery of high frequency QPO in low-mass X-ray binaries

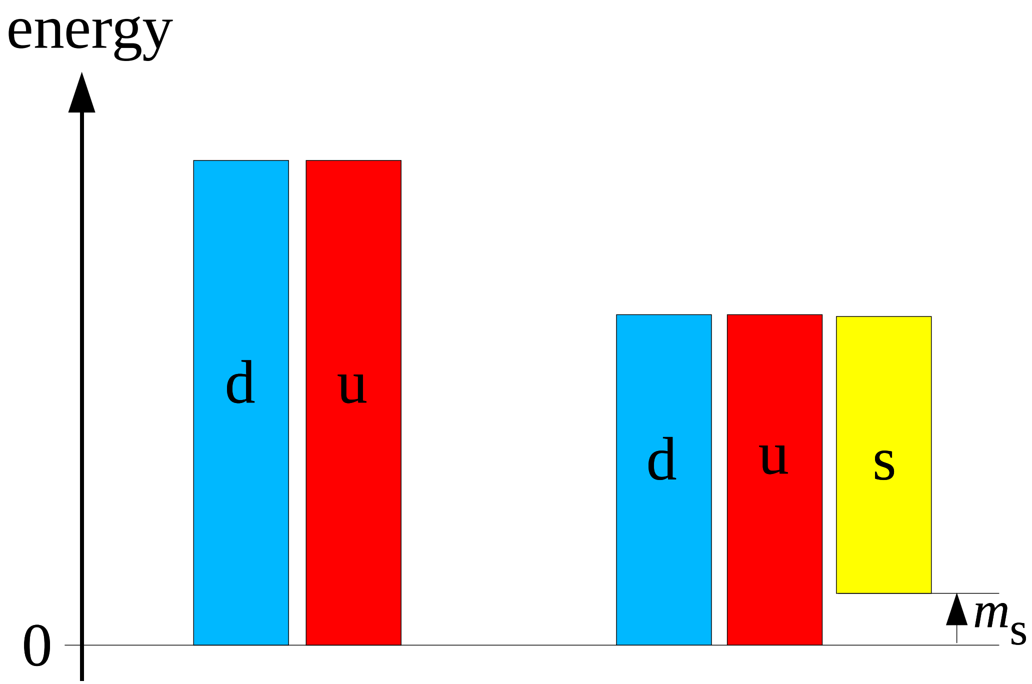
2002 : NASA announcement of “discovery” of two strange quark stars

Ground state of hadronic matter



Why non-zero strangeness ?

Quarks are **fermions:**



Pauli exclusion principle $\Longrightarrow$ 3-flavor quark matter has a lower energy than 2-flavor quark matter.

Approximate treatment of QCD

Complexity of QCD $\Longrightarrow$ a direct computation of the quark matter EOS is not doable.

The simplified approach to quark matter EOS:

- describe non-perturbative aspects of QCD (**quark confinement** and **asymptotic freedom**) by a very simplified phenomenological model: **the MIT bag model;**
- describe perturbative effects (**quark interactions** within the bag) by an expansion in $\alpha_{\mathrm{s}} = g^2/(4\pi)$, where g is the QCD coupling constant .

2

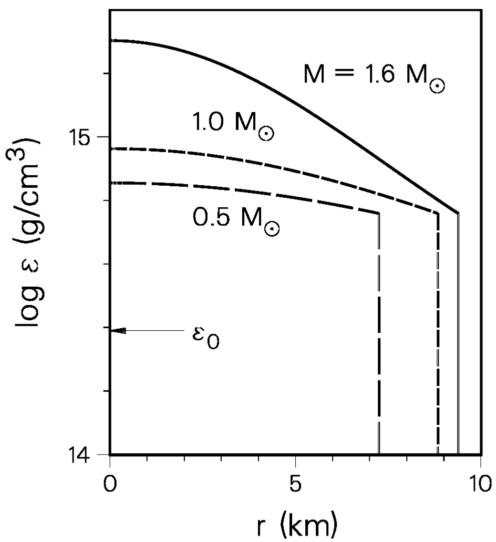
Numerical models of strange quark stars

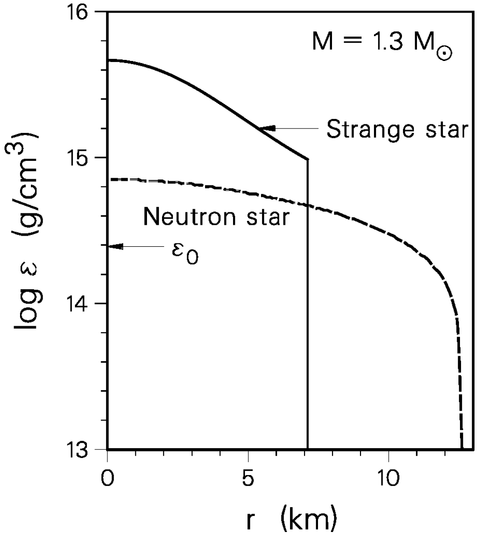
Static strange stars

First numerical models computed by Haensel, Zdunik & Schaeffer [A&A **160**, 121 (1986)] and Alcock, Fahri & Olinto [ApJ **310**, 261 (1986)] by integration of the **Tolman-Oppenheimer-Volkoff equations** with MIT bag-model EOS.

Basic features:

- finite density at the surface (zero pressure)
- for small mass (weak gravity): almost constant density profile $\varepsilon \sim 4B$

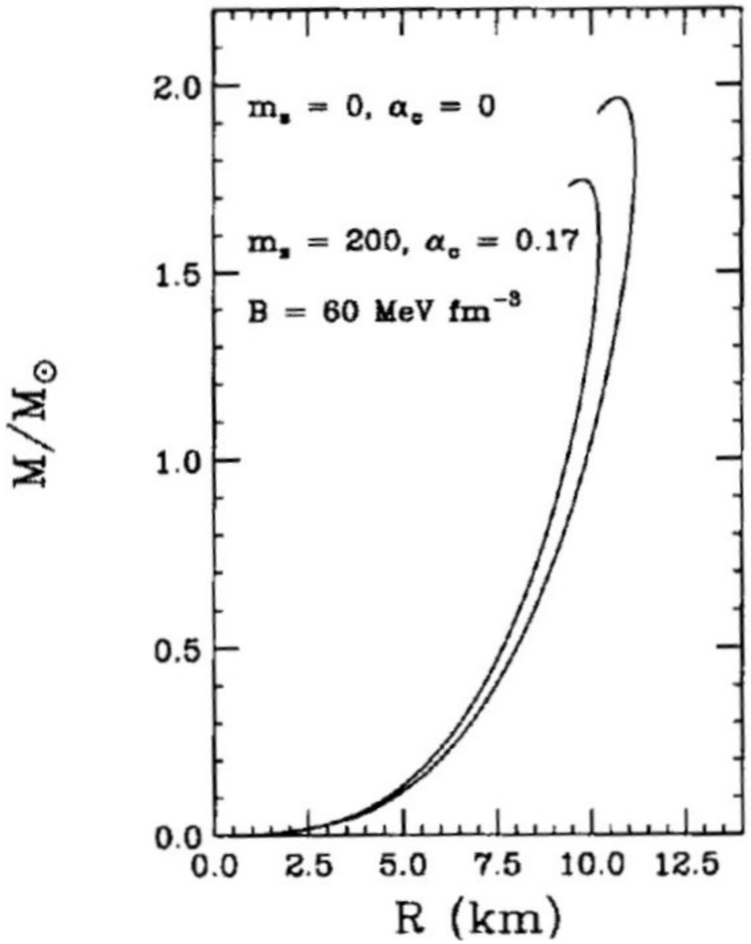




[from Glendenning (1997)]

Mass-radius relation

From strangelets to strange stars



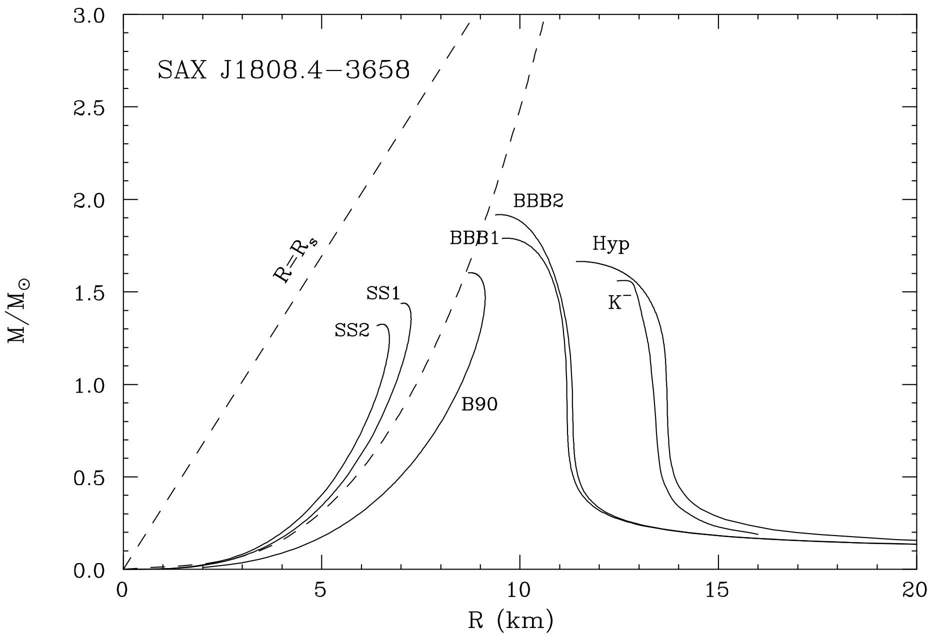
Gravitational mass as a function of the areal radius for nonrotating strange stars in the MIT bag model [from Bombaci (2001)]

Approximate scaling laws (exact for $\alpha_{\mathrm{s}} = 0$) [Zdunik, A&A **359**, 311 (2001)] :

$$M \simeq M\left[B_{60} = 1, \alpha_{\mathrm{s}}, m_{\mathrm{s}} {B_{60}}^{-1/4}\right] \ {B_{60}}^{-1/2}$$

$$R \simeq R\left[B_{60} = 1, \alpha_{\mathrm{s}}, m_{\mathrm{s}} {B_{60}}^{-1/4}\right] \ {B_{60}}^{-1/2}$$

Comparison with neutron stars

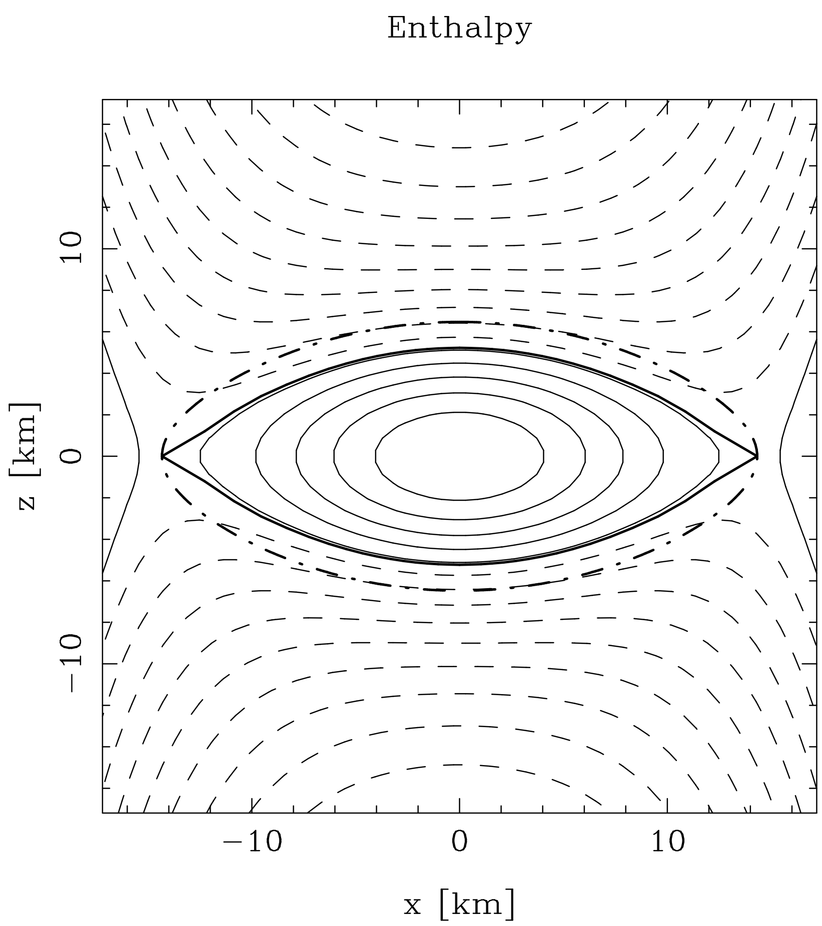


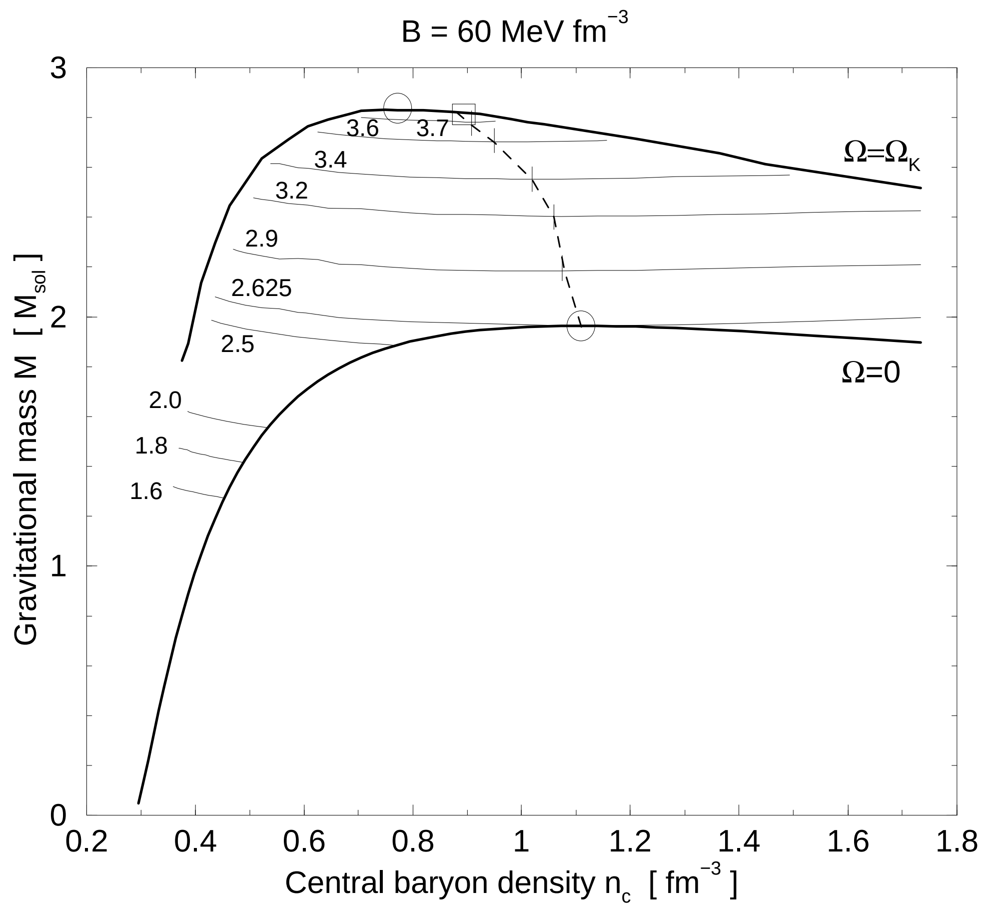
Gravitational mass as a function of the areal radius for nonrotating neutron stars (BBB1, BBB2, Hyp and K^-) and nonrotating strange stars in the MIT bag model (B90) and Dey et al model (SS1 and SS2) [from Bombaci (2002)]

neutron stars = gravitationally bound objects

strange quark stars ∼ self-bound objects

Rotating strange quark stars

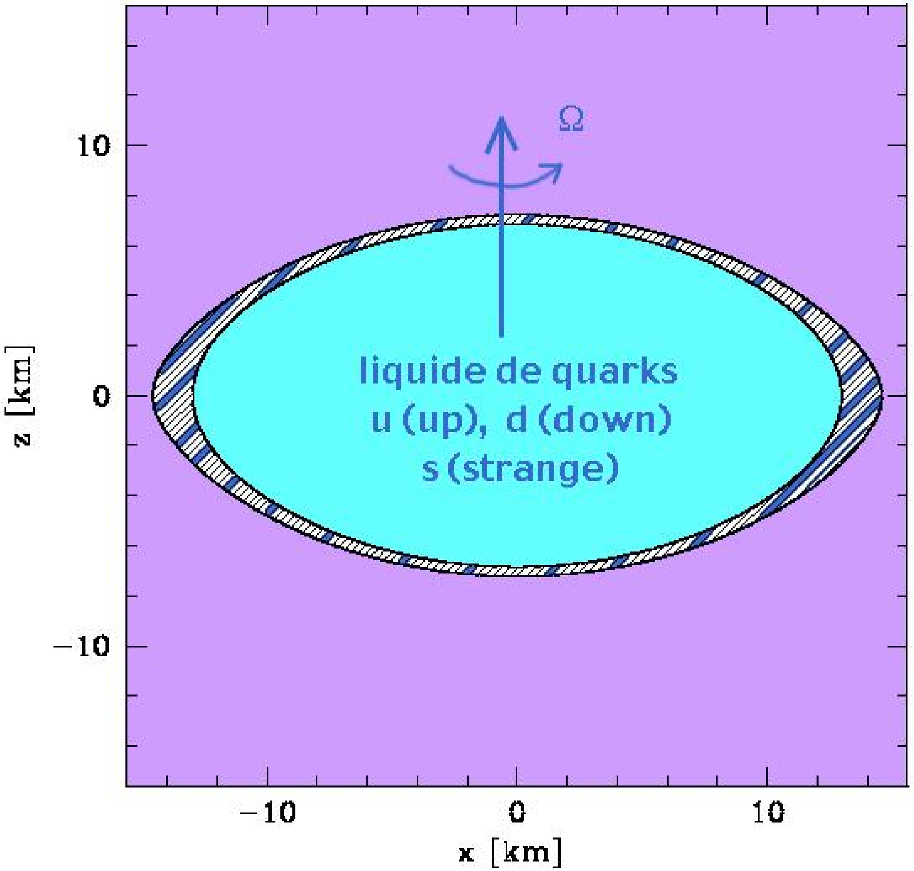


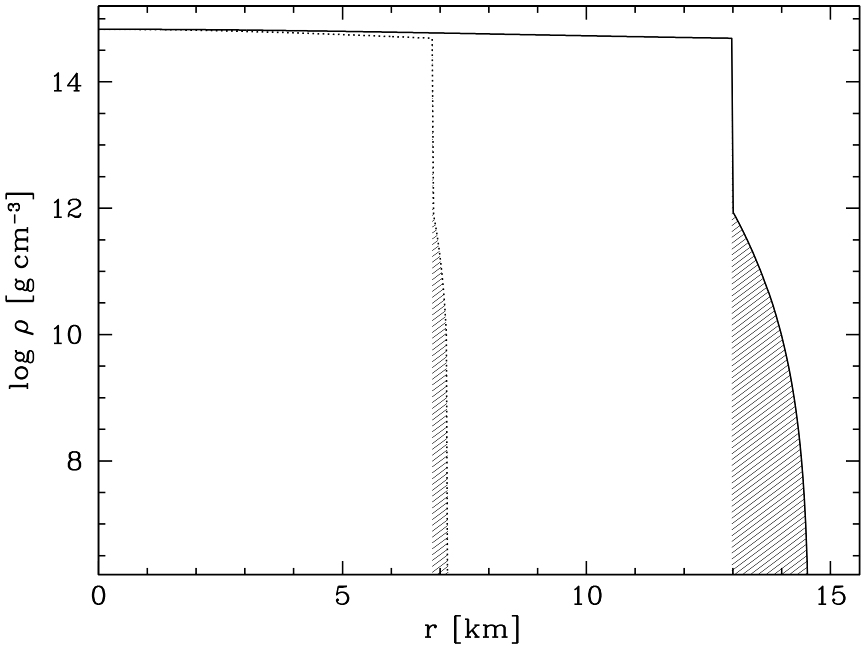


[from Gourgoulhon et al., A&A **349**, 851 (1999)]

Minimal rotation period (for $m_s = 0$ and $\alpha_s = 0$): $P_{\rm min} = 0.634\, B_{60}{}^{-1/2}$ ms

Solid crust



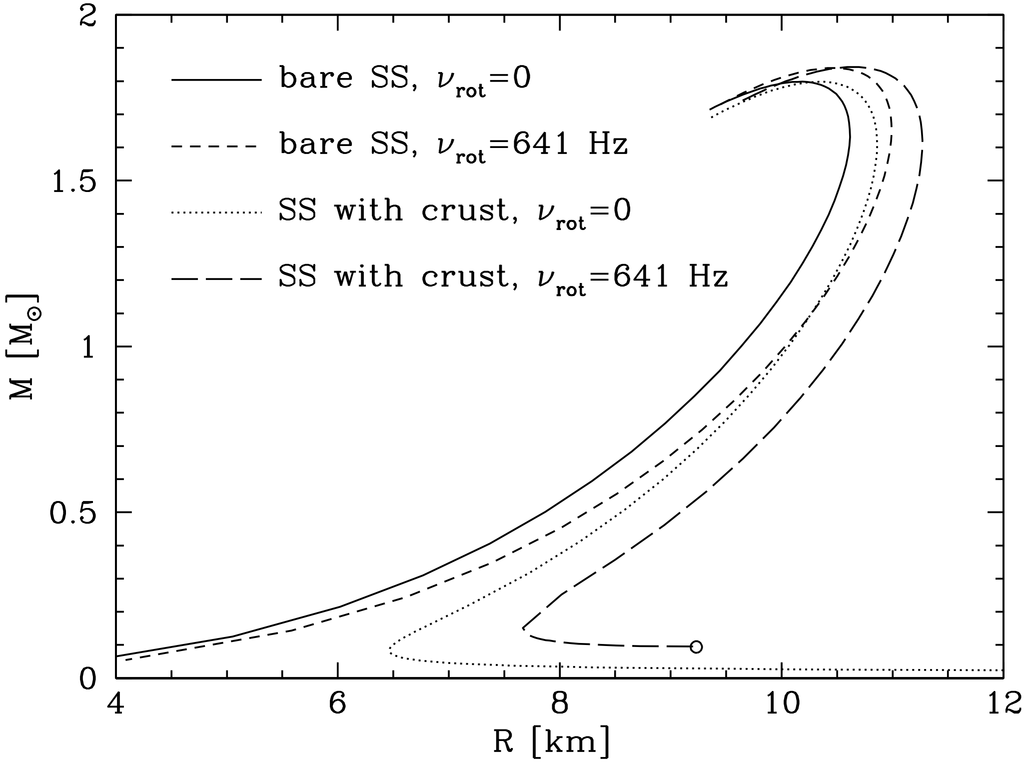


EOS: $B = 56\ \mathrm{MeV\,fm}^{-3}$, $\alpha_\mathrm{s} = 0.2$, $m_\mathrm{s} = 200\ \mathrm{MeV}\,c^{-2}$
star: $M_\mathrm{B} = 1.63\,M_\odot$, $f = 1210\ \mathrm{Hz}$.

[from Zdunik, Haensel, Gourgoulhon, A&A **372**, 535 (2001)]

Stellar radius in presence of crust

There exists a minimal radius:

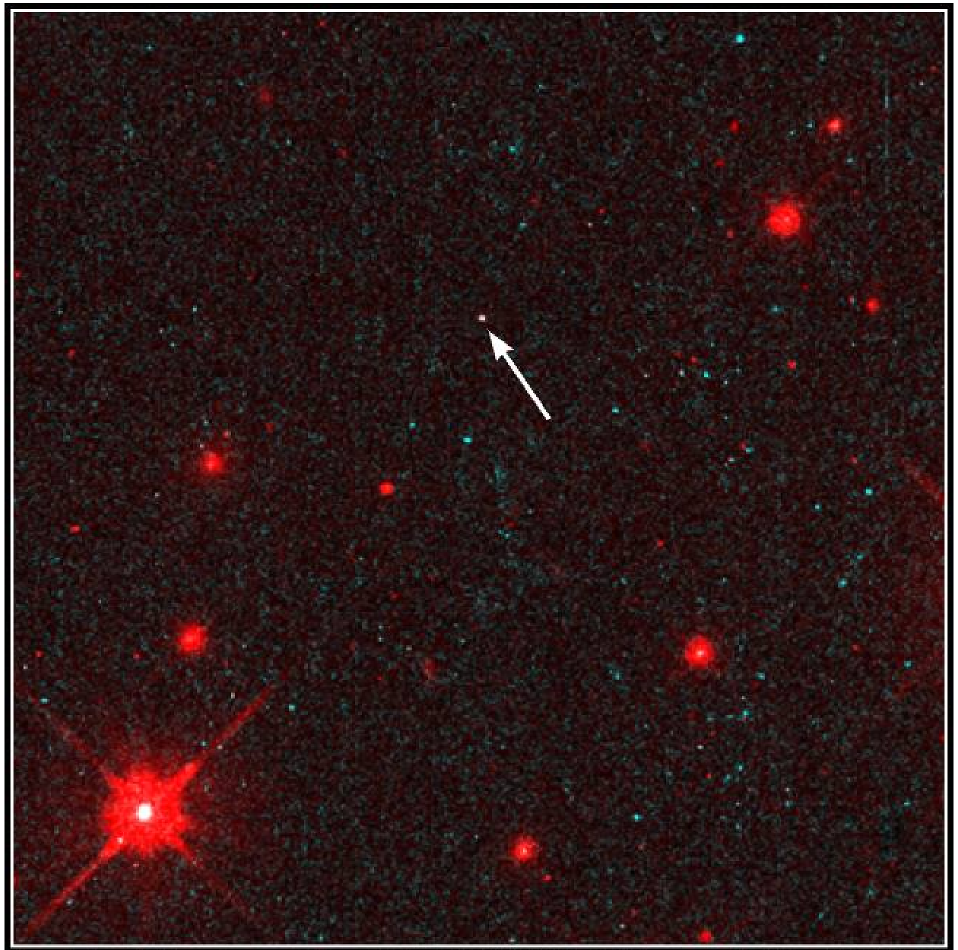


[from Zdunik, Haensel, Gourgoulhon, A&A **372**, 535 (2001)]

3

Chandra observations

RX J1856.5-3754

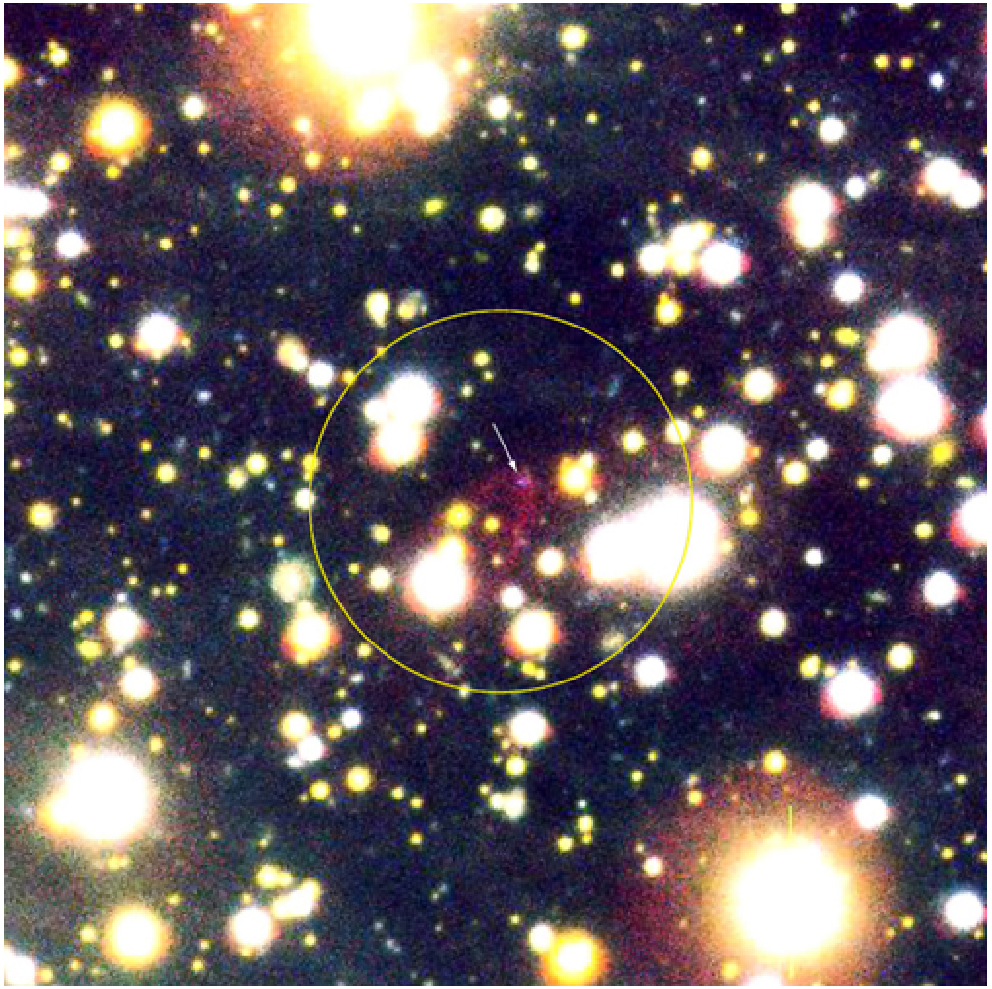


Isolated Neutron Star RX J185635-3754 HST • WFPC2
PRC97-32 • ST ScI OPO • September 25, 1997
F. Walter (State University of New York at Stony Brook) and NASA

- Discovered as an X-ray source with ROSAT in 1996 [Walter et al., Nature **379**, 233 (1996)]
Best fit black body $kT_\infty = 57 \pm 1\ \mathrm{eV}$
$\Longleftrightarrow T_\infty \simeq 6.6 \times 10^5\ \mathrm{K}$
In front of molecular cloud *R Coronae Australis* $\Rightarrow d \lesssim 130 - 170\ \mathrm{pc}$

- Optical counterpart discovered in 1997 with HST [Walter & Matthews, Nature **389**, 358 (1997)]
magnitude $V = 25.6$
Optical flux 2 to 3 times larger than the tail of the $57\ \mathrm{eV}$ black body

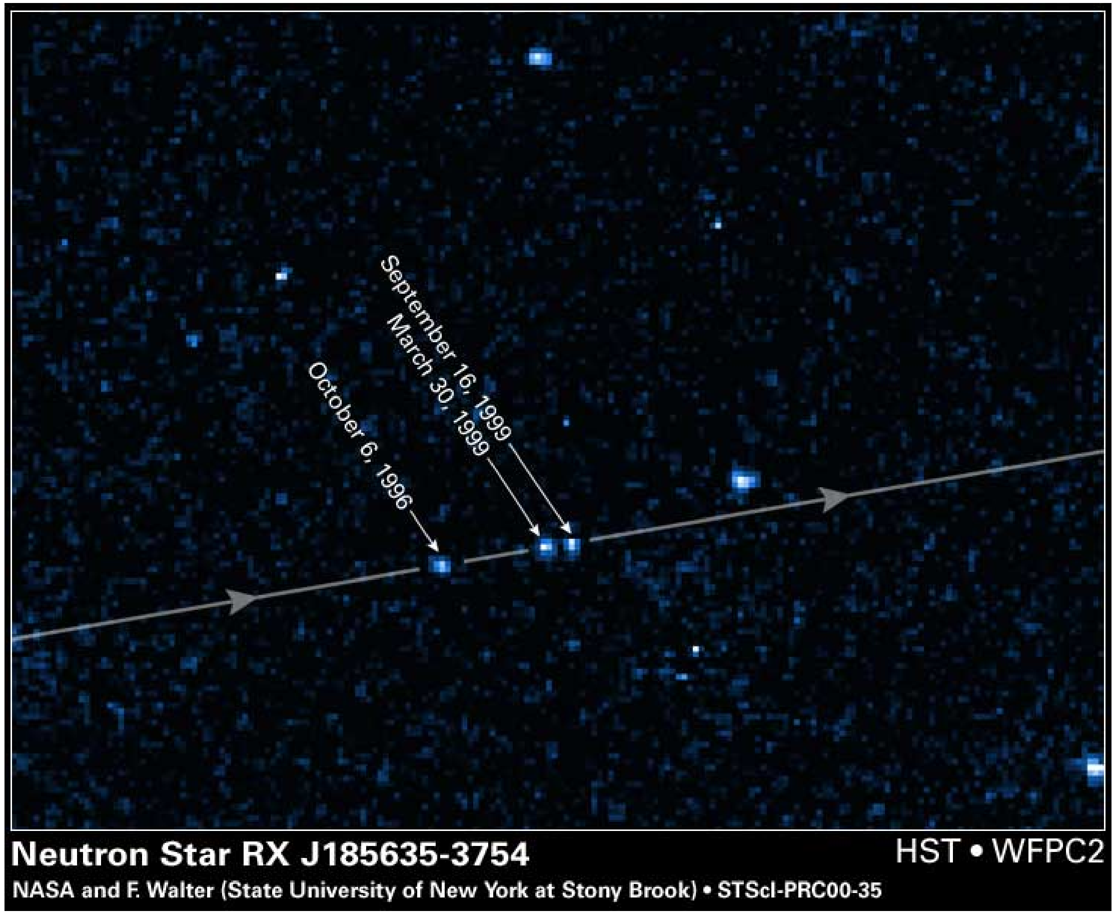
RX J1856.5-3754 observed by VLT



VLT Kueyen + FORS2 (field: $80" \times 80"$)

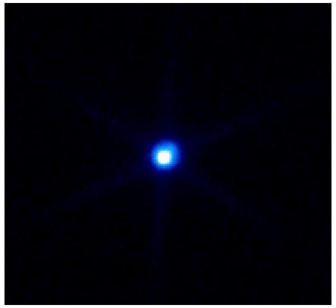
$\rightarrow$ bowshock (heated interstellar gas by accelerated e^- and p from the star ?) [ESO 2000]

Distance to RX J1856.5-3754

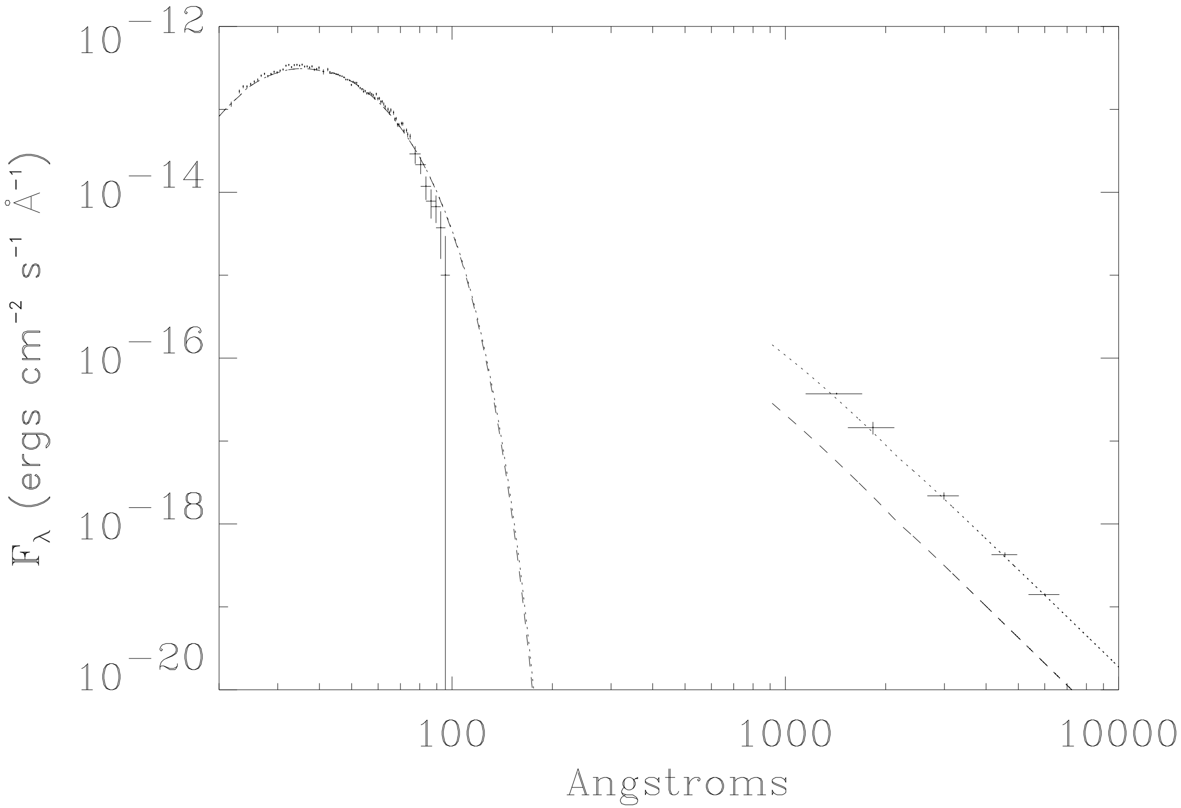


- First measure of proper motion and parallax (erroneous) [Walter, ApJ **549**, 433 (2001)]
  $\Rightarrow$ erroneous $d = 61 \pm 9$ pc
- New determinations of parallax:
  $d = 140 \pm 40$ pc [Kaplan, van Kerkwijk, Anderson, astro-ph/0111174]
  $d = 117 \pm 12$ pc [Walter & Lattimer, astro-ph/0204199]

RX J1856.5-3754 spectrum



Chandra image of RX J1856.5-3754



Spectrum from Chandra, EUVE and HST data:

- - - - : black body best fit to Chandra data $kT_\infty = 63$ eV [Burwitz et al., A&A **379**, L35 (2001)]

.........: 63 eV black body + 15 eV black body with $R_\infty(15 \text{ eV}) = 5R_\infty(63 \text{ eV})$

[from Walter & Lattimer, astro-ph/0204199]

Simple estimation of radius from black body emission

Observed quantities: (at infinite distance from the star)

- electromagnetic flux f_∞
- surface temperature T_∞ (black body fit to the spectrum)
- distance d (parallax)

Estimation of the radius:

Total luminosity for black body emission: $L_\infty = 4\pi R_\infty^2 \sigma T_\infty^4$

Flux on Earth: $f_\infty = \frac{L_\infty}{4\pi d^2} = \left(\frac{R_\infty}{d}\right)^2 \sigma T_\infty^4$

Hence the radius "measured" at infinity: $\boxed{R_\infty = \frac{d}{T_\infty^2}\left(\frac{f_\infty}{\sigma}\right)^{1/2}}$

Relation between R_∞ and the true radius of the star R

Areal radius of the star (surface value of the Schwarzschild coordinate r): R

Redshift factor at the surface of the star: $N = \sqrt{-g_{00}} = \left(1 - \frac{2GM}{c^2 R}\right)^{1/2}$

Gravitational dilation of time: $dt_\infty = N^{-1} dt$ (N : *lapse function*)

Energy and wavelength of a particle reaching infinity: $E_\infty = NE$ and $\lambda_\infty = N^{-1}\lambda$

Luminosity at infinity: $L_\infty = \frac{dE_\infty}{dt_\infty} = N^2 \frac{dE}{dt} = N^2 L$

Local black body emissivity: R areal radius $\Rightarrow L = 4\pi R^2 \sigma T^4$

"Observed" temperature: $\lambda_{\max} T = \mathrm{const.} \Rightarrow T_\infty = NT$

Observed black body: $L_\infty = 4\pi R_\infty^2 \sigma T_\infty^4$

Hence $R_\infty = N^{-1} R$, i.e. $\boxed{R_\infty = \left(1 - \frac{2GM}{c^2 R}\right)^{-1/2} R}$

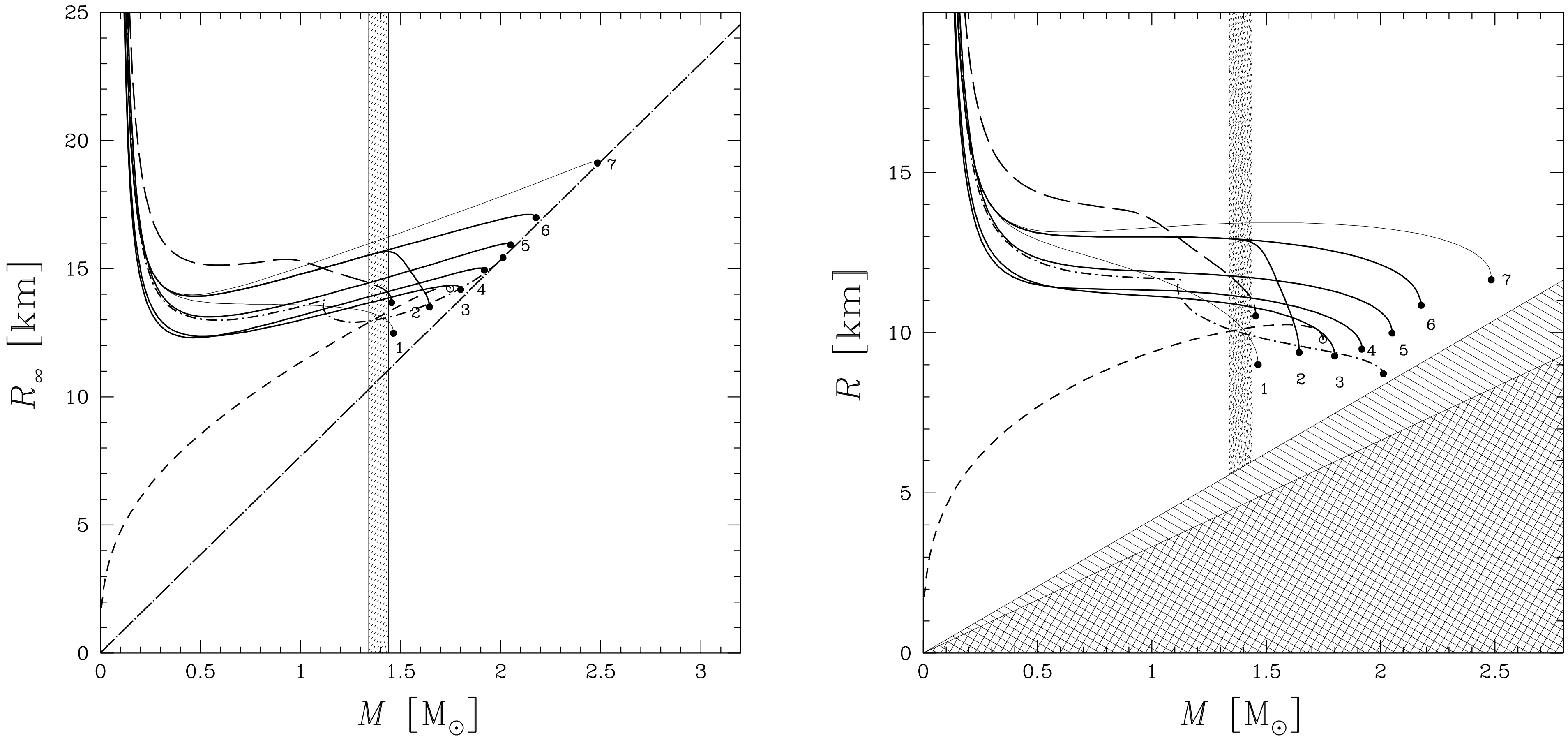
The very small radius puzzle

- Erroneous distance of Walter 2001 : $d = 61$ pc $\Rightarrow R_\infty = 3.3$ km (for $f_\infty^{\rm ROSAT}$ and $kT_\infty = 57$ eV).

- New distance of Walter & Lattimer 2002 : $d = 117$ pc $\Rightarrow R_\infty = 4.8$ km (for $f_\infty^{\rm Chandra}$ and $kT_\infty = 61$ eV).

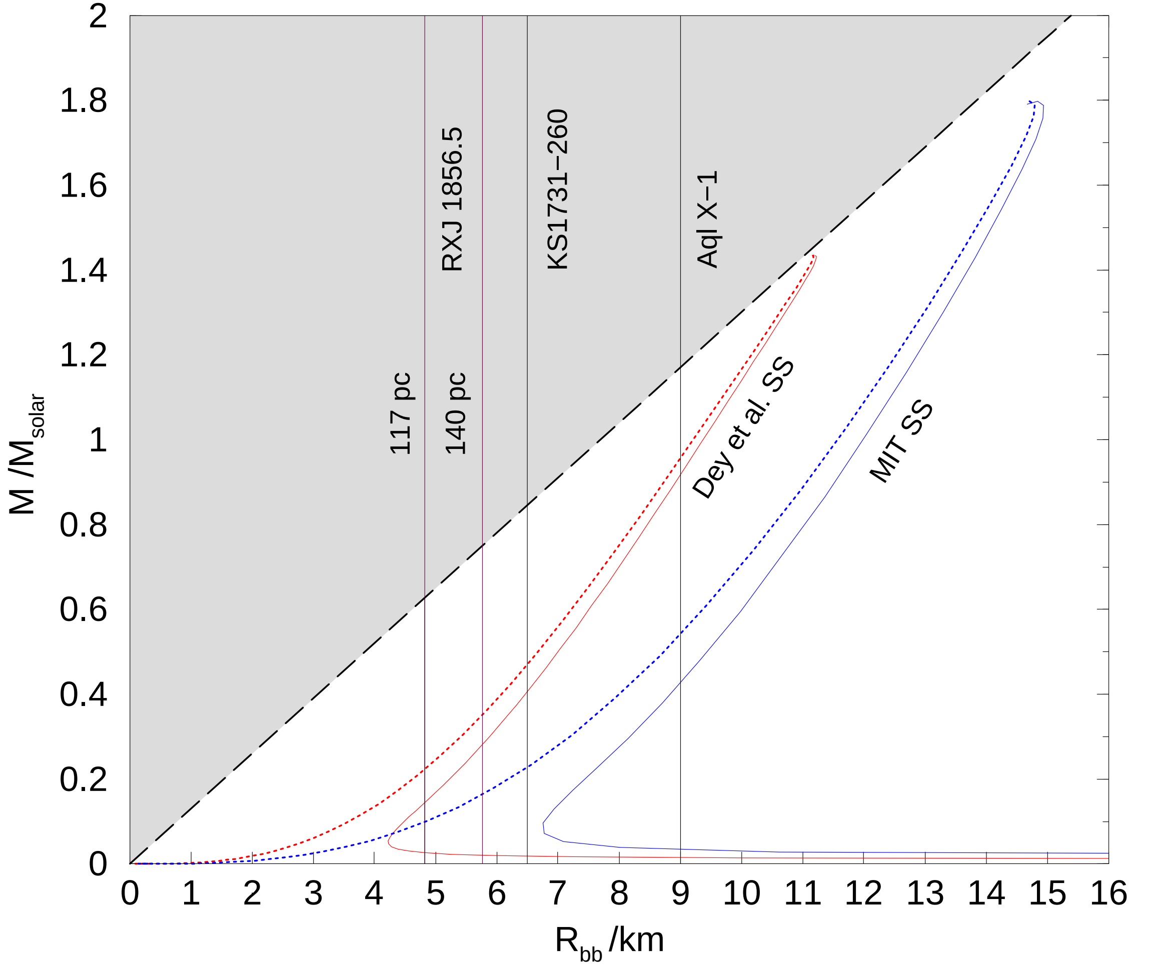
- New distance of Kaplan et al. 2002 : $d = 140$ pc $\Rightarrow R_\infty = 5.8$ km (for $f_\infty^{\rm Chandra}$ and $kT_\infty = 61$ eV).

Minimal radius of neutron stars



Solid lines: neutron star models; *dashed line:* strange quark star with MIT bag model EOS: $B = 41$ MeV fm^{-3}, $m_s = 150$ MeV c^{-2}, $\alpha_s = 0.6$ [from Haensel, A&A **380**, 186 (2001)].

Minimal radius of strange quark stars



[from Gondek-Rosińska, Kluźniak & Stergioulas, astro-ph/0206470 (2002)]

A proposed solution

Pons et al. [ApJ **564**, 981 (2002)] : the emission is not a pure black body one.

Two atmospheric models:

1. Uniform temperature + heavy elements (Fe)

2. Two thermal components (optical flux from cooler part)

Model 1 $\Rightarrow R_\infty \simeq 15\ \mathrm{km}$ for $d = 117\ \mathrm{pc}$, $f_\infty^{\mathrm{ROSAT}}$ and $kT_\infty = 57\ \mathrm{eV}$

Model 2 $\Rightarrow R_\infty \simeq 21\ \mathrm{km}$ for $d = 117\ \mathrm{pc}$, $f_\infty^{\mathrm{Chandra}}$ and $kT_\infty = 63\ \mathrm{eV}$

[Walter & Lattimer, astro-ph/0204199]

Recent Chandra observations

Drake et al. [ApJ **572**, 996 (2002)] have conducted deep observations of RX J1856.5-3754 in October 2001 (446 ks of data).

Findings:

- X-ray spectrum well represented by a black body spectrum with $kT_\infty = 61.2 \pm 1.0$ eV ($T_\infty = 7.1 \times 10^5$ K)
- no heavy element spectral lines $\Rightarrow$ disfavors atmospheric model 1 of Pons et al. (2002)
- no X-ray pulsation (pulse fraction $< 2.7\%$) $\Rightarrow$ disfavors atmospheric model 2 of Pons et al. (2002)

Inferred pure black body radius: $R_\infty = 4.12 \pm 0.68 \text{ km} \dfrac{d}{100 \text{ pc}}$

Has a strange quark star been discovered ?

Maybe, but one should remain cautious:

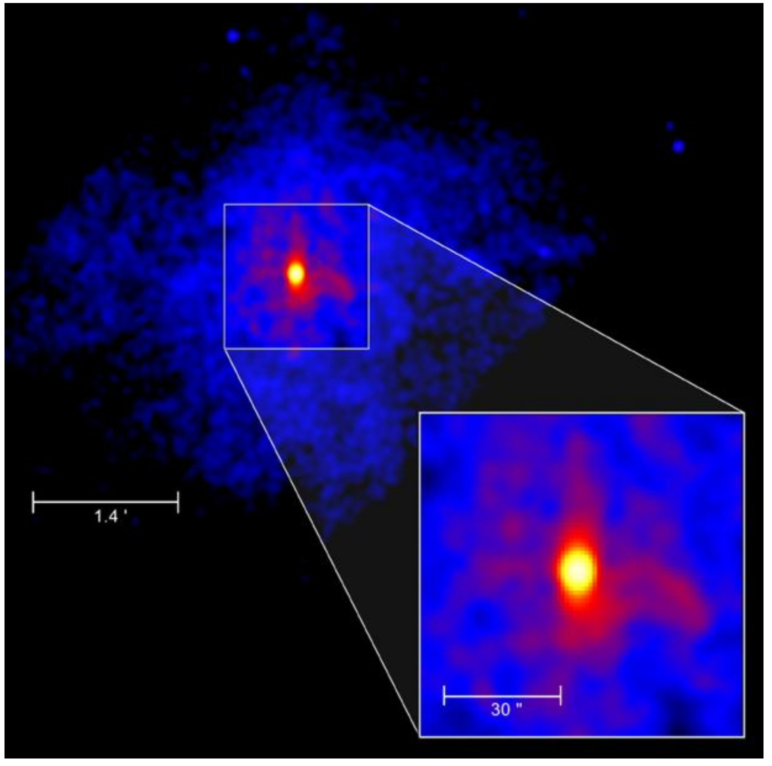
- extrapolation of the ~ 61 eV black body spectrum to low frequencies underpredicts the optical flux by a factor 6 [Walter & Lattimer, astro-ph/0204199]
- disagreement between Chandra flux and ROSAT one: $f_{\mathrm{Chandra}} \sim 0.8 f_{\mathrm{ROSAT}}$
- $R_\infty = 5.8$ km ($d = 140$ pc) implies a maximum mass of only $\sim 0.7\, M_\odot \Rightarrow$ how to form such light star ?

A possible answer proposed by Nakamura [astro-ph/0205526] :
Gravitational collapse of a very rapidly neutron star with Kerr parameter J/M^2 larger than 1 does not lead to a black hole but to a small mass quark star + a jet. In addition this provides a source for gamma ray bursts !

The second strange star candidate: 3C 58

3C 58: remnant of the supernova SN 1181 (younger than Crab nebula: SN 1054)

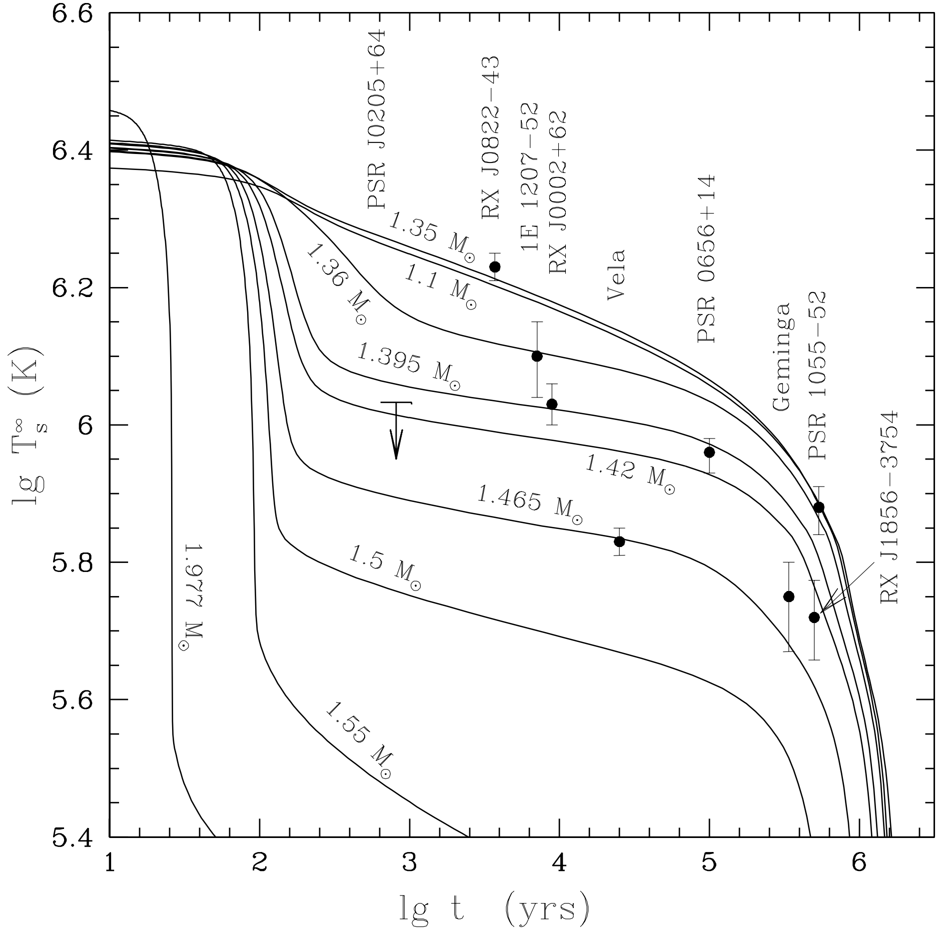
Central object: X-ray and radio pulsar PSR J0205+6449, $P = 65\ \mathrm{ms}$, discovered by Chandra observations [Murray et al., ApJ **568**, 226 (2002)]



Argument for a strange quark star: $T_\infty < 1.1 \times 10^6\ \mathrm{K}$, too cold for a neutron star 820 years old [Slane, Helfand, Murray, ApJ **571**, L45 (2002)]

...but this argument is not conclusive !

Many alternatives are possible within cooling theories of ordinary neutron stars:



[from Yakovlev, Kaminker, Haensel, Gnedin, astro-ph/0204233]

Conclusions and perspectives

- From our (poor) knowledge of strong interaction, it is not inconceivable that **strange quark matter** constitutes the ground state of cold dense matter.

- A class of compact stellar objects, bound by strong interaction (in addition to gravity), would then constitute an alternative to neutron stars: **strange quark stars**.

- Strange quark stars have some features (small radius, large break-up rotation velocity, location of ISCO, etc...) than make them **observationally distinguishable** from neutron stars.

- Discovering a strange quark star would be an extremely valuable contribution of **astrophysics** to **particle physics**.

- From the two claims of discovery based on recent Chandra observations, of **RX J1856.5-3754** can be considered as providing a strange quark star serious candidate. It has to be **confirmed** by further observational studies.

Conclusions and perspectives (cont'd)

- If RX J1856.5-3754 is confirmed as a strange star, there remains to explain the formation of such a **small mass** object.
- Since RX J1856.5-3754 is one of the closest compact stars, it would be then likely that **most, if not all, compact stars are actually strange quark stars**.
- A strong support for the possible existence of strange quark star would be the discovery of **strangelets** in the next generation of ultra-relativistic heavy ion colliders (RHIC at Brookhaven, LHC at CERN).