The Neutron Star Crust and Surface
June 28, 2007

Constraints on Dense Matter from X-ray Observations of Neutron Stars

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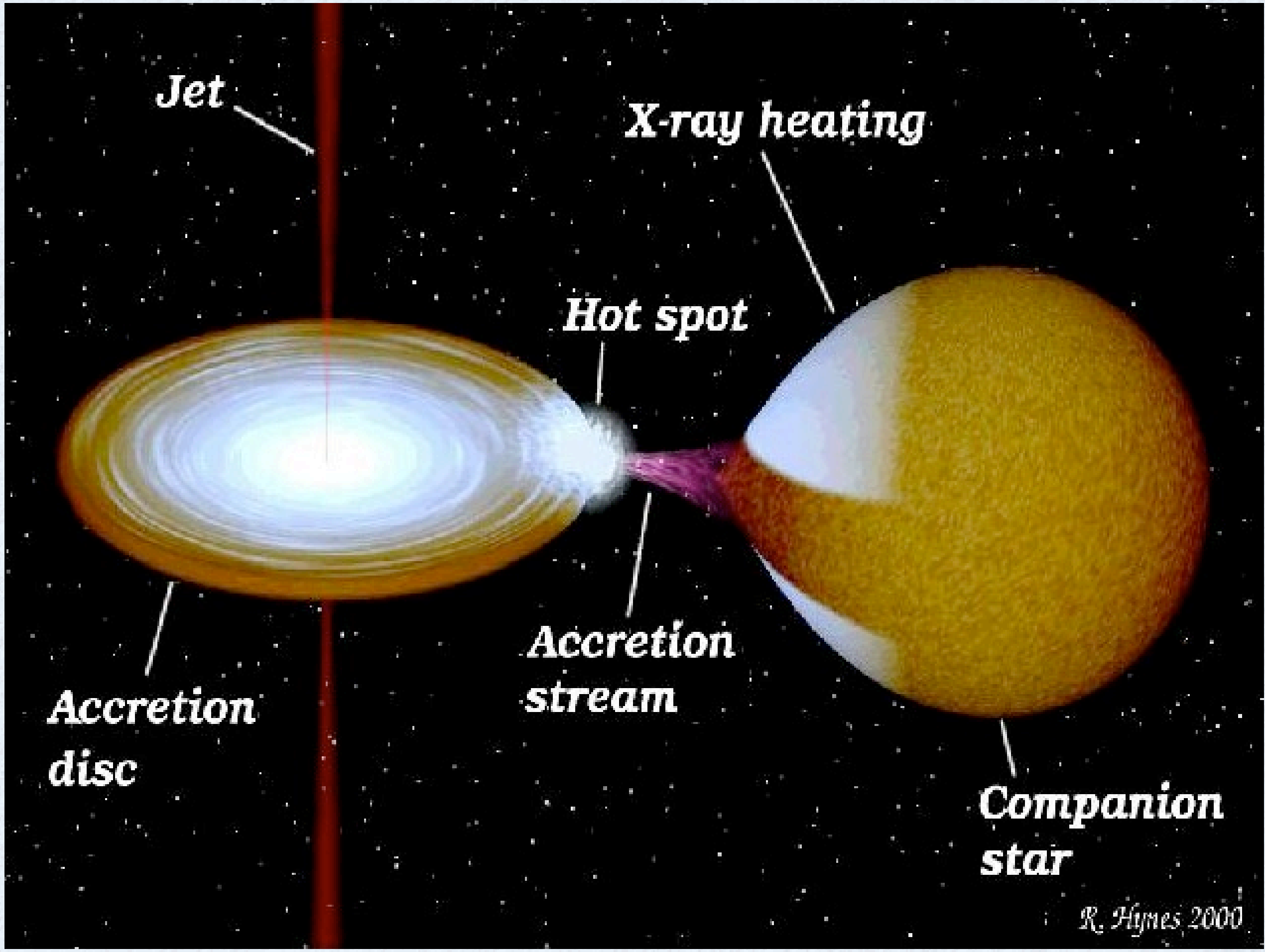
X-Ray Binaries

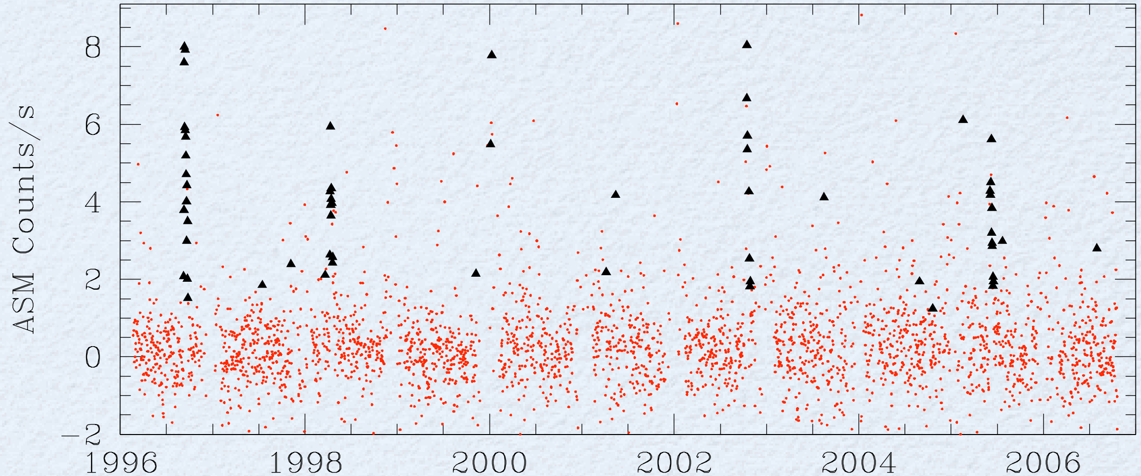
- Neutron star (NS) accretes mass from companion
- Incoming matter produces accretion disk
- Roughly 100 NSs accreting at high rates in Galaxy



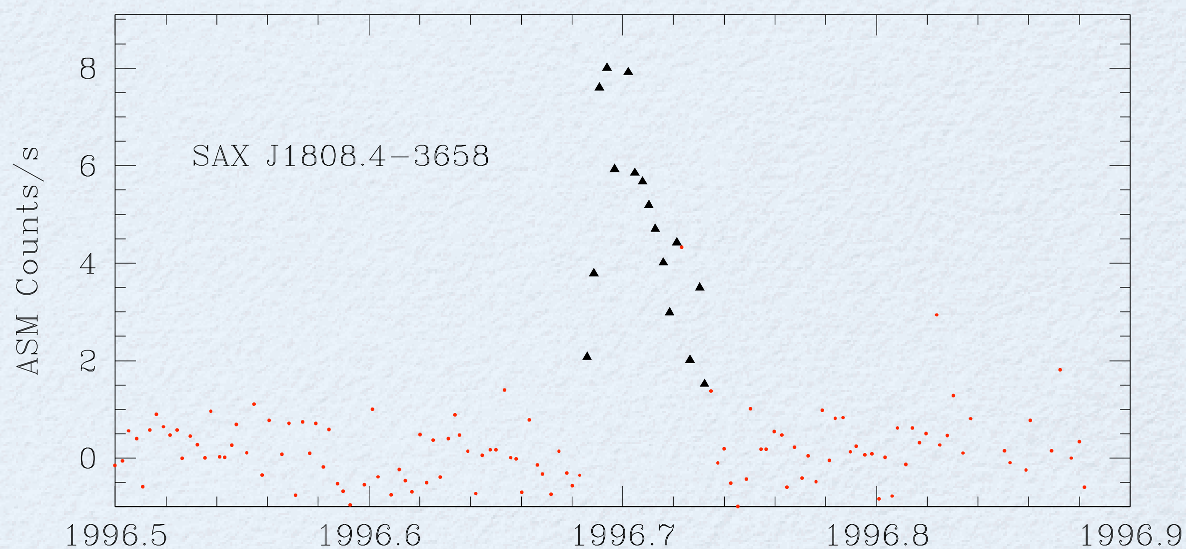
Low-mass X-ray binary (LMXB)

X-Ray Binary Transients

- Brief outbursts, most of disk falls onto neutron star
- Disk builds up during long quiescent periods
- Quiescent X-ray flux 10^3-10^5 times fainter than outburst; little or no accretion

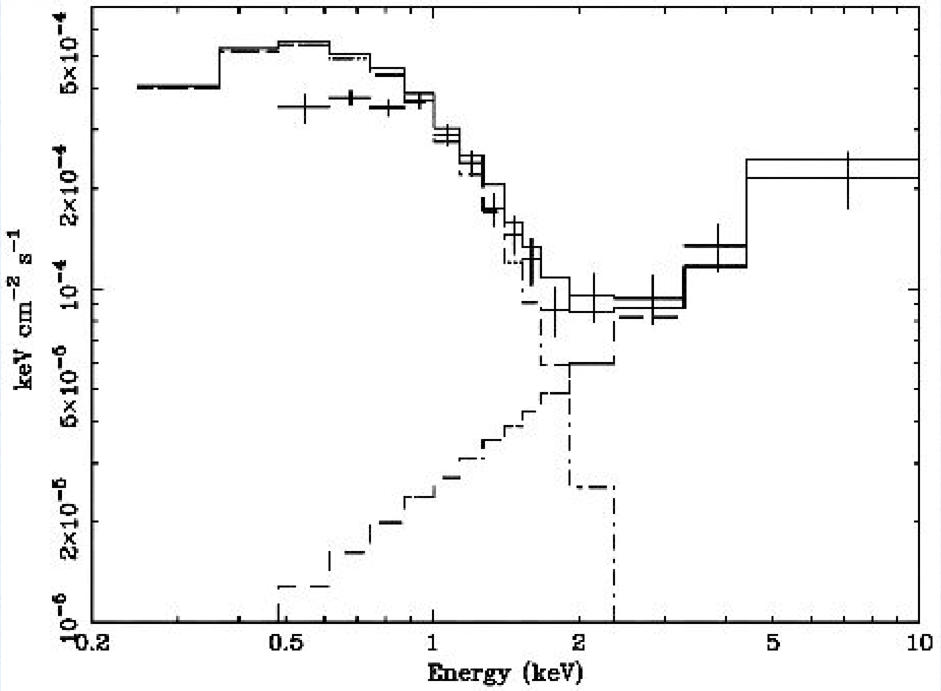


RXTE ASM



Quiescence

- X-ray spectrum shows: blackbody-like emission from surface; high-energy emission (nature unknown); photoelectric absorption at low energy
- Blackbody-like emission modeled as radiation of whole surface through hydrogen atmosphere



X-ray spectrum of Cen X-4 in quiescence, Rutledge 01

H-Atmosphere Models

- Assume pure ionized H, B<10^9 G: adequate for kT~100 eV quiescent NS. Atmosphere fractionates within seconds.
- Models computed by Zavlin & Pavlov, Rybicki in very close agreement. Well-understood case.
- Possible uncertainties:
  - Low-level accretion (alter opacity with traces C,O,N; e.g. Rutledge 02a)
  - White dwarf companion-> He atmosphere
  - Temperature inhomogeneities?

A: Radius Constraints

- Can constrain radius of blackbody if know flux, temperature, distance (Brown 98)
- Flux=$\sigma(R/D)^2 T_{eff}^4$
- Must correct for redshift of light from neutron star surface, giving constraint on mass and radius. Surface gravity effects on spectrum mean confidence contours don't perfectly track R_∞.
- Distance rarely known accurately in galaxy, except in globular clusters--Rutledge 02b for ω Cen.

Globular clusters

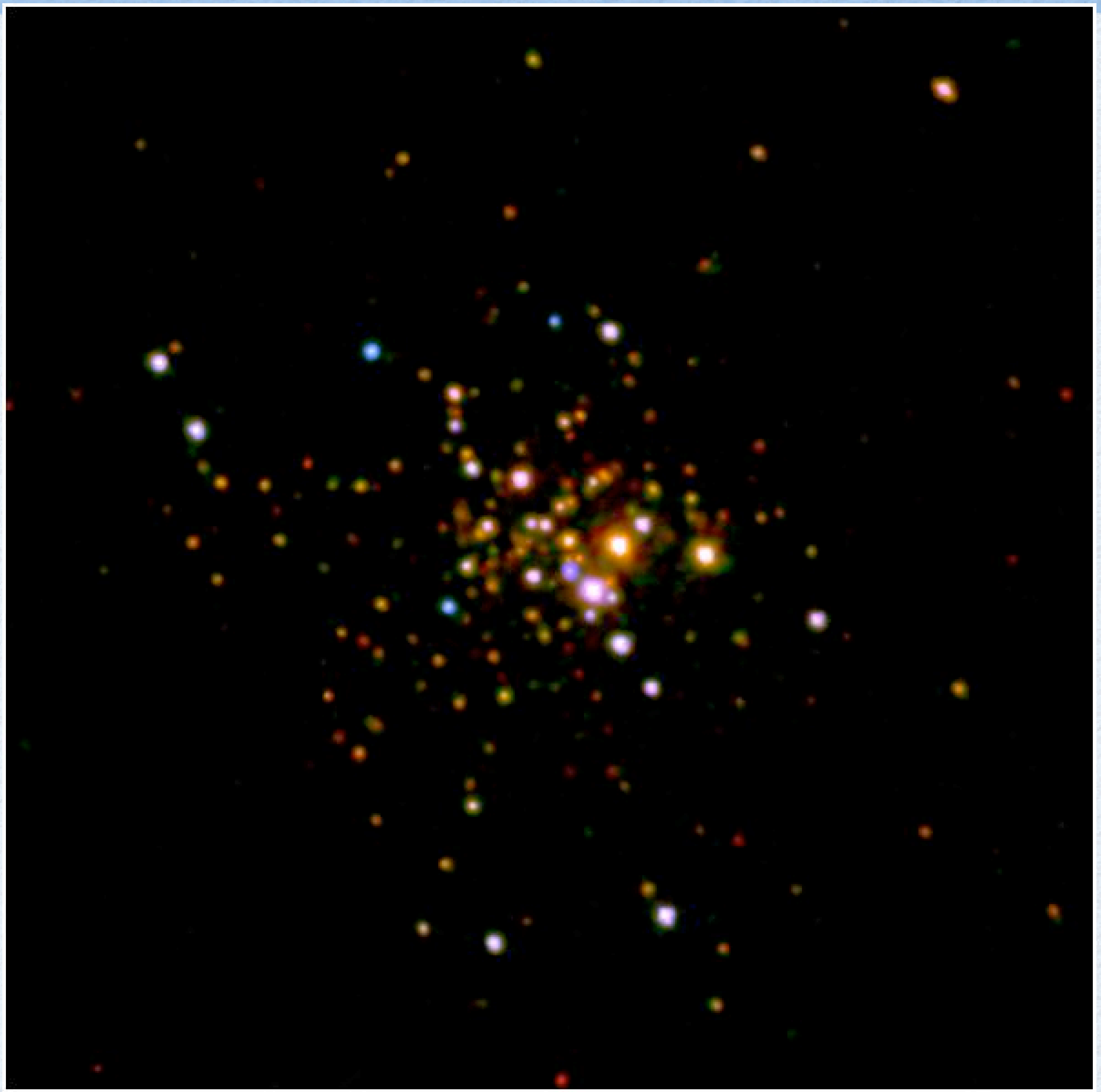
HST image of 47 Tuc

- Dense clusters of 10^{4-7} stars of same age, composition
- Distance can be well constrained (currently to ~10%)
- Extremely dense core, leading to stellar interactions
- Stellar collisions or exchanges, putting many neutron stars into close binaries

R. Gilliland, Hubble on 47 Tuc

47 TUCANAE

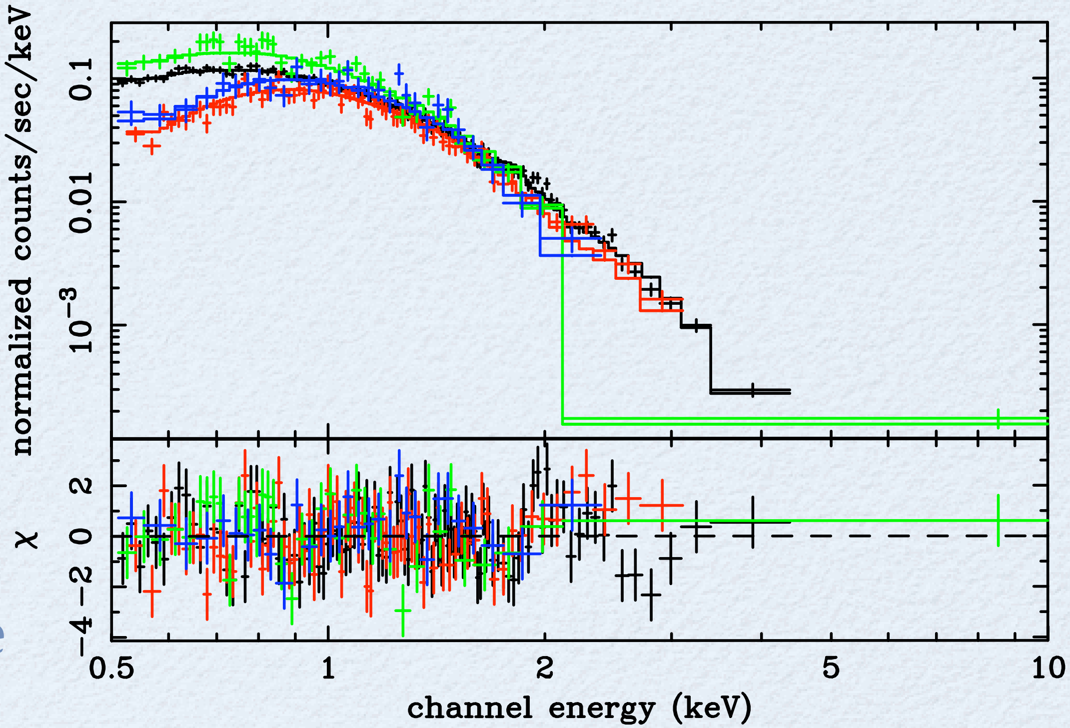
- Chandra X-ray studies find dozens of X-ray binaries in quiescence, 5 in this deep image of 47 Tuc
- Brightest (X7) shows blackbody-like spectrum without second component
- Second brightest also blackbody-like spectrum, eclipses at 8.7 hours, binary optical counterpart detected



Chandra on 47 Tuc, Heinke 05

X7 Spectrum

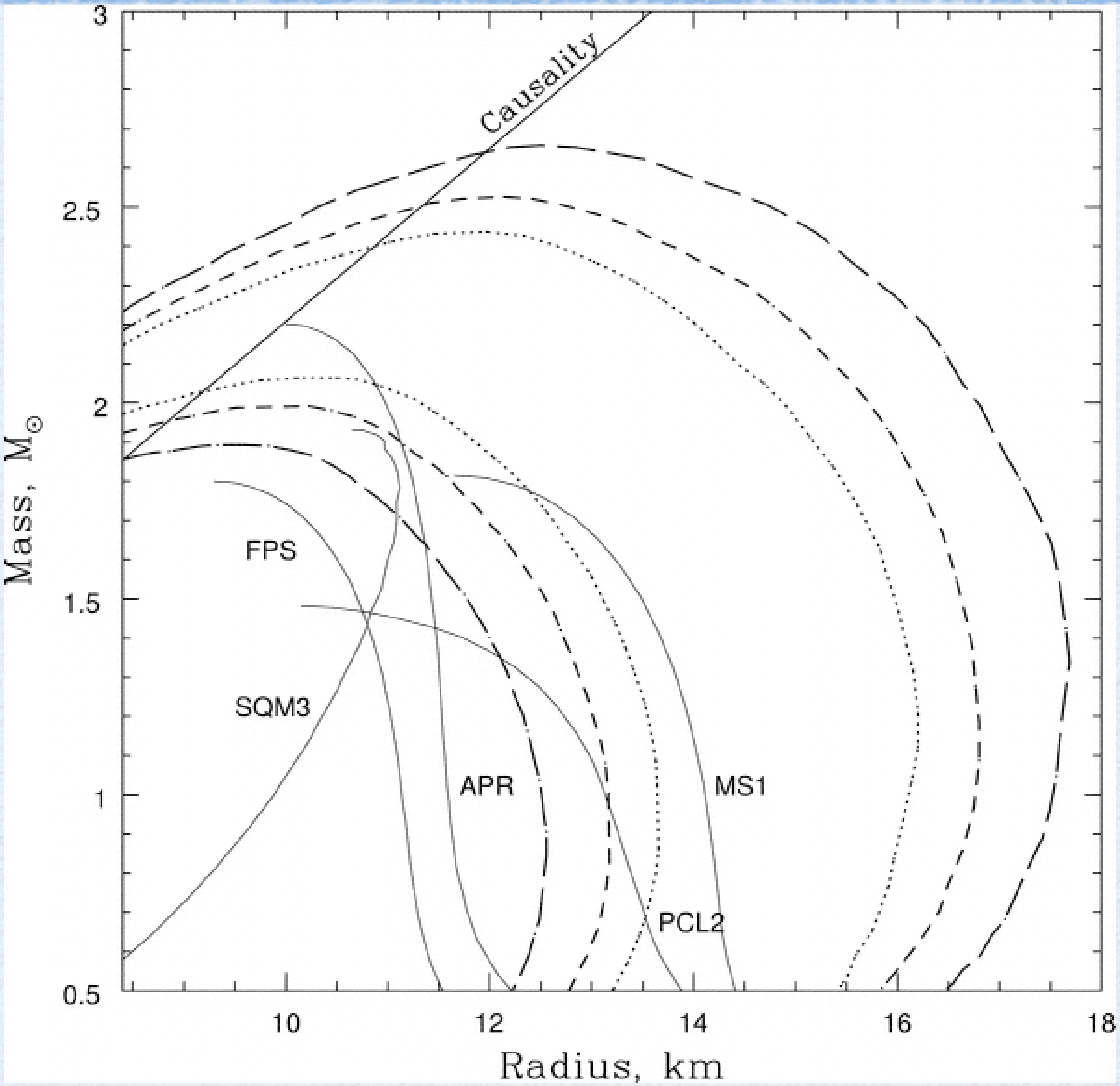
- Excellent fit to H-atmosphere
- No evidence for lines, edges
- No variability (hours to decades), no evidence for accretion
- Temp. inhomogeneities testable with long Chandra HRC dataset
- Perfect test object!!



Chandra X-ray spectrum, Heinke 06

X7 Mass, Radius

- Spectral fit to X7 places constraints on M, radius
- Indicates moderately large radius, excluding several NS structures
- XMM measurements of other NSs find slightly smaller radii (Gendre 03)



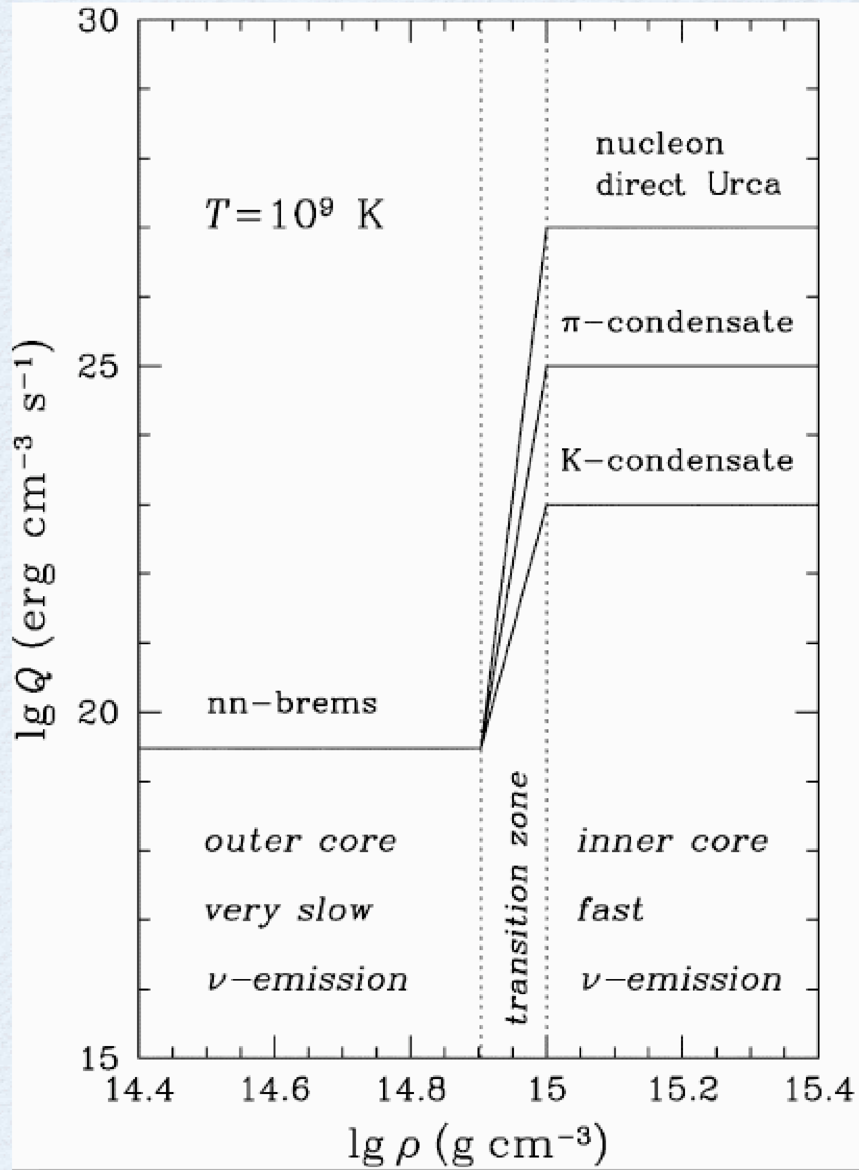
90%, 2σ, 3σ contours; Heinke 06

B: Cooling of Neutron Stars

- During accretion, outer crust heated, quickly radiates heat (see Ed Cackett's talk).
- Deep crust under pressure fuses nuclei, heats core (Brown 98).
- Heat from core emitted from surface in quiescence, on timescale of 10^4 years, at rate ~1/130 of time-averaged flux from accretion under minimal cooling (see K. Levenfish's talk for details).
- Well-studied transient LMXBs provide constraints on cooling rate, neutrino emission, NS interior structure.

Cooling Neutron Stars

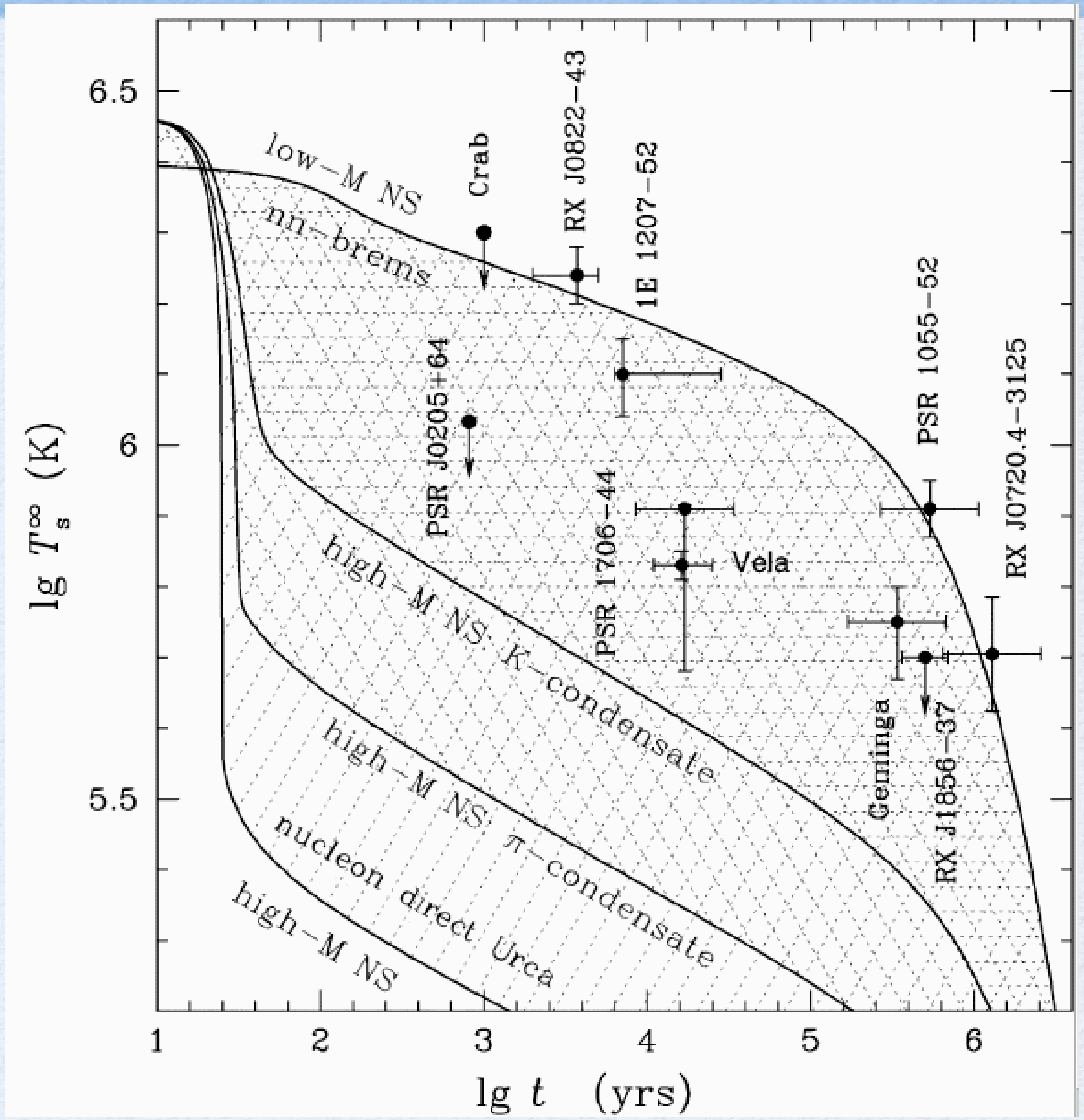
- "Standard" neutrino cooling in low-mass neutron stars through neutron-neutron bremsstrahlung
- Higher mass neutron stars can reach higher neutrino emissivity
- E.g., direct URCA process: n→p+e+ν, p+e→n+ν, if protons >10%
- Proton superconductivity prevents direct URCA processes, decays with increasing density, allowing **range of cooling rates for range of NS masses**



Yakovlev & Pethick 04

Cooling thru exotica

- Compare young cooling NSs with cooling predictions
- Hottest NS agree with standard cooling
- Coolest NSs consistent with any enhanced cooling mechanism



Yakovlev & Pethick 2004

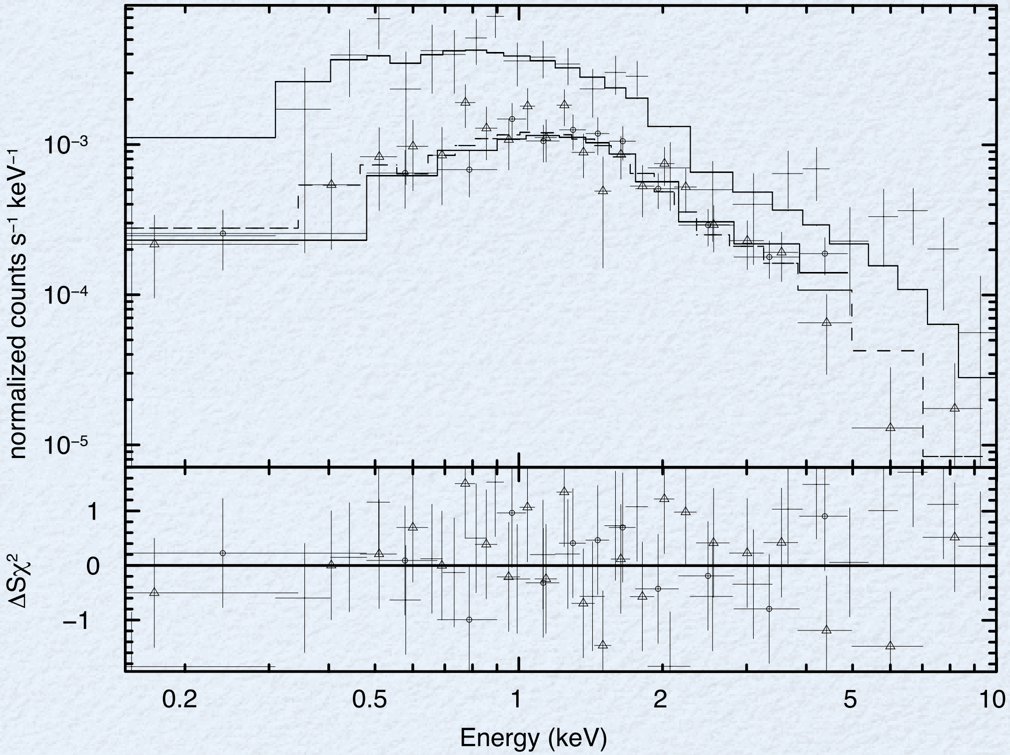
SAX J1808.4-3658

- Equivalent measurement for transient LMXBs, IF mass transfer rate and quiescent temperature measured.
- NSs in X-ray binaries can accrete substantial mass. Greater range in masses, greater range in cooling rates?
- SAX J1808.4-3658: Regular outbursts (every ~2 years), known distance (3.4-3.6 kpc; Galloway 06) -> known mass transfer rate
- Perfect agreement with predictions of mass transfer rate from gravitational radiation.
- Allows accurate quiescent flux prediction!

SAX J1808.4-3658

- X-ray spectrum well-fit with power-law, with no blackbody component
- Constrains neutron star temperature < 34 eV (<$4*10^5$ K), $L_{bol,NS} < 10^{31}$ erg/s
- Most restrictive constraint on neutron star cooling

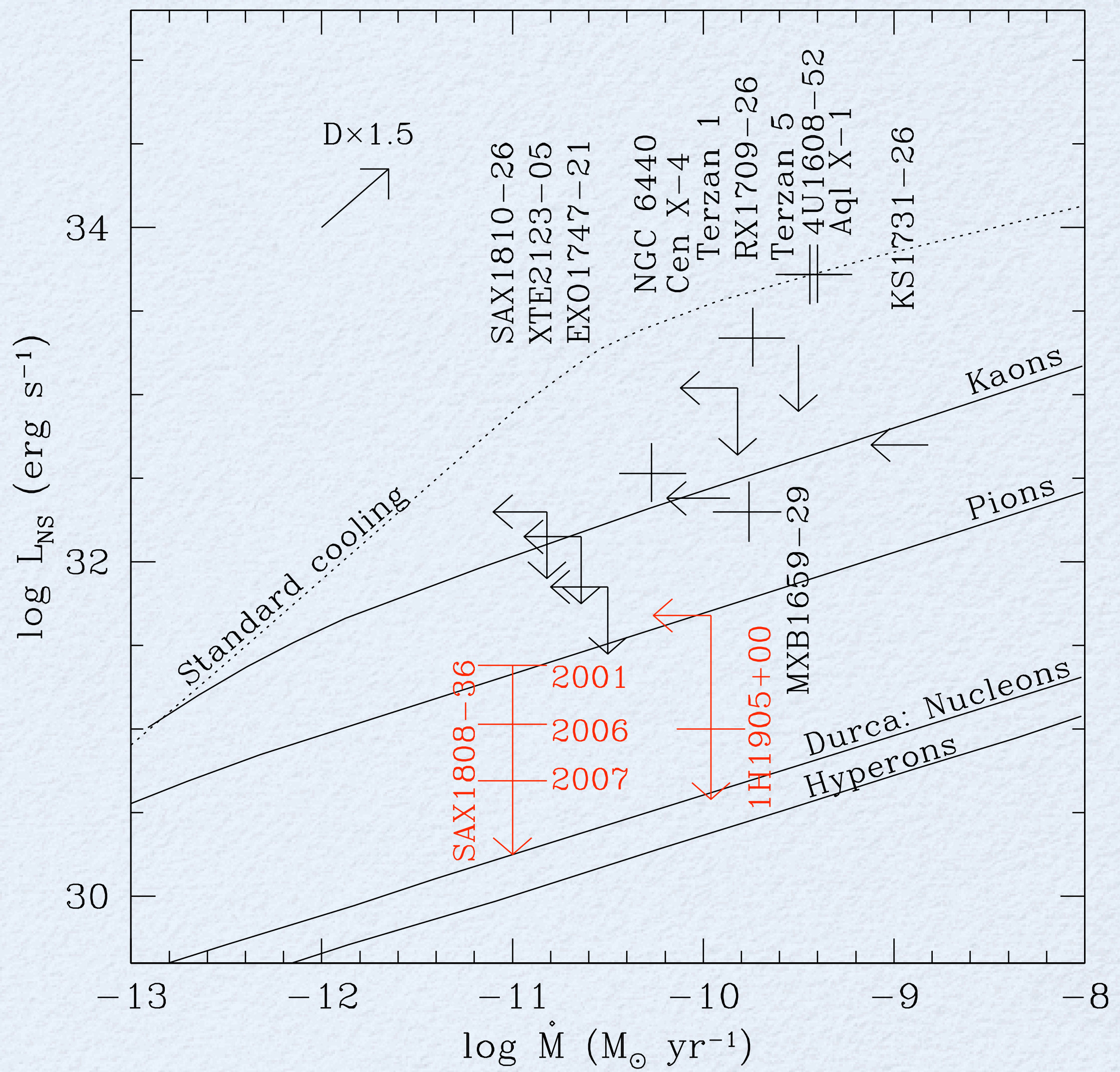
New 2007 observation: kT<30 eV, $L_{bol,NS} < 5*10^{30}$ erg/s



X-ray spectra and residuals, Heinke et al. 2007

Cooling Constraints

- SAX J1808-36 cools quickly, likely has large mass
- 1H 1905+000 (Jonker 07) also cold (kT<39 eV, $L_{bol,NS}<10^{31}$ erg/s)
- Suggests direct URCA, by nucleons or hyperons; may reject minimal cooling



Luminosity vs. mass transfer rate, Heinke et al. 2007 (updated)

Conclusions

- X-ray observations of LMXBs in quiescence provide constraints on behavior of dense matter
- Radius measurements of NS in 47 Tuc suggests moderately large radius or high mass
- SAX J1808.4-3658 and 1H 1905+000 require very fast cooling, disagree with minimal cooling

Future Observations

- More globular cluster quiescent LMXBs available:
  Webb re-analysis of XMM observations in revision,
  deep NGC 6397 Chandra observations occurring this week.
  Constellation-X will give spectacular results!
- Many more transient NSs available for study; distance measurements crucial (need Type 1 bursts--RXTE critical!)
- Would LOVE to have a cooling rate measurement AND a mass for several (even one) NSs!

FOR BOB

- To tell physicists (and other astronomers):

- Zero-B hydrogen-atmosphere models are **trustworthy**!

- M,R constraints from NSs in globular clusters are **sound**, beginning to reach interesting constraints.

- Cooling constraints from some transient LMXBs are strictest test of core cooling, and **disallow minimal cooling**.

FOR BOB

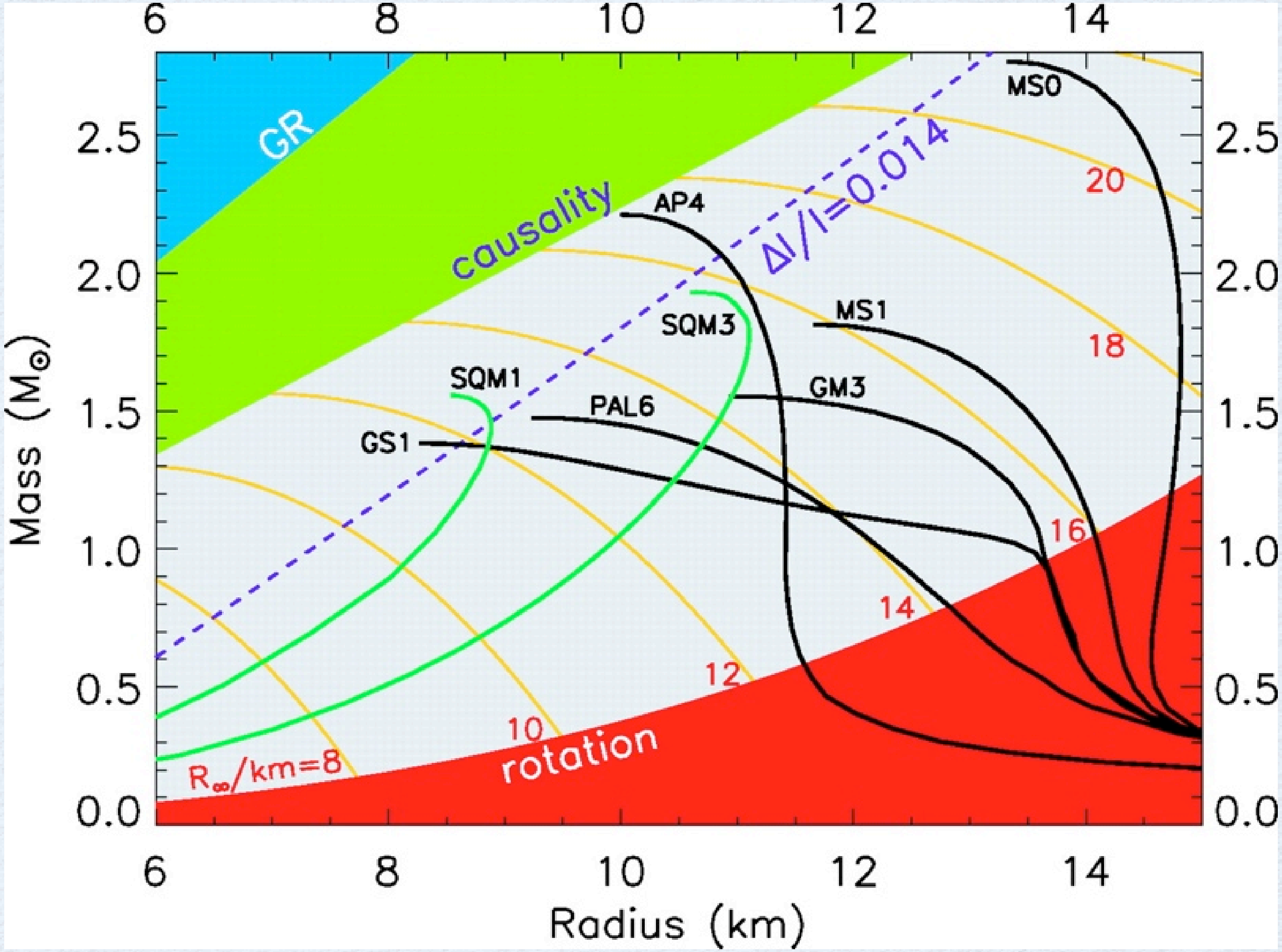
- To ask nuclear theorists:

- What range of nuclear EOSs are considered reasonable?
  For a measured NS mass and radius, what is really ruled out?

- What are the real ranges of cooling rates for different NS interior properties; i.e. can pion condensates explain the coldest NSs?

Equations of State

- Proton-rich nucleus gives large maximum mass, radius (MS0)
- Kaons, pions etc. can reduce P, give small radius (GS1, PAL6)
- Shaded regions excluded
- Constraining mass and radius important



Lattimer & Prakash 2004

Transient LMXB observations

Table 2. **Luminosities and Mass Transfer Rates**

Source	N_H (10^{22} cm^{-2})	kT (eV)	D (kpc)	Outbursts	Years	$\dot{M}$ ($M_\odot$ yr^{-1})	L_{NS} (erg s^{-1})	Refs
Aql X-1	4.2×10^{21}	~94	5	8	10.7	4×10^{-10}	5.3×10^{33}	1,2,3,4
Cen X-4	5.5×10^{20}	76	1.2	-	-	$< 3.3 \times 10^{-11}$	4.8×10^{32}	5,3
4U1608–522	8×10^{21}	170	3.6	4	10.7	3.6×10^{-10}	5.3×10^{33}	6,3,4
KS 1731–260	1.3×10^{22}	70	7	1	30	$< 1.5 \times 10^{-9}$	5×10^{32}	7,4
MXB 1659–29	2.0×10^{21}	55	~10?	2	10.7	1.7×10^{-10}	2.0×10^{32}	7,4
EXO 1747–214	4×10^{21}	< 63	< 11	-	-	$< 3 \times 10^{-11}$	$< 7 \times 10^{31}$	8
Terzan 5	1.2×10^{22}	< 131	8.7	2	10.7	3×10^{-10}	$< 2.1 \times 10^{33}$	9,10,4
NGC 6440	7×10^{21}	87	8.5	3	35	1.8×10^{-10}	3.4×10^{32}	11,4
Terzan 1	1.4×10^{22}	74	5.2	-	-	$< 1.5 \times 10^{-10}$	$< 1.1 \times 10^{33}$	12
XTE2123–058	6×10^{20}	< 66	8.5	1	10.7	$< 2.3 \times 10^{-11}$	$< 1.4 \times 10^{32}$	3,4
SAXJ1810.8–2609	3.3×10^{21}	< 72	4.9	1	10.7	$< 1.5 \times 10^{-11}$	$< 2.0 \times 10^{32}$	13,3,4
RXJ1709–2639	4.4×10^{21}	122	8.8	2	10.7	1.8×10^{-10}	2.2×10^{33}	14,15,4
1H1905+000	1.9×10^{21}	< 50	10	-	-	$< 1.1 \times 10^{-10}$	$< 4.8 \times 10^{31}$	16,15
SAXJ1808.4–3658	1.3×10^{21}	< 34	3.5	5	10.7	1.0×10^{-11}	$< 1.1 \times 10^{31}$	17,4,15

Note. — Estimates of quiescent thermal luminosities from neutron star transients, and mass transfer rates (inferred from RXTE ASM observations for systems with RXTE-era outbursts). Quiescent thermal luminosities are computed for the unabsorbed NS component in the 0.01-10 keV range. Outbursts and years columns give