Thermonuclear Bursts from Millisecond Pulsars: Matching Observations with Models

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Background image source: NASA/Goddard Space Flight Center/Dana Berry

Accretion Powered Millisecond Pulsars

- Neutron stars in a binary system
- Accreting matter from a low mass companion star.
- Weak magnetic fields ($\sim 10^8$ G)
- Typically transient X-ray sources
- Exhibit coherent X-ray pulsations
- Exhibit type I thermonuclear bursts periodically.

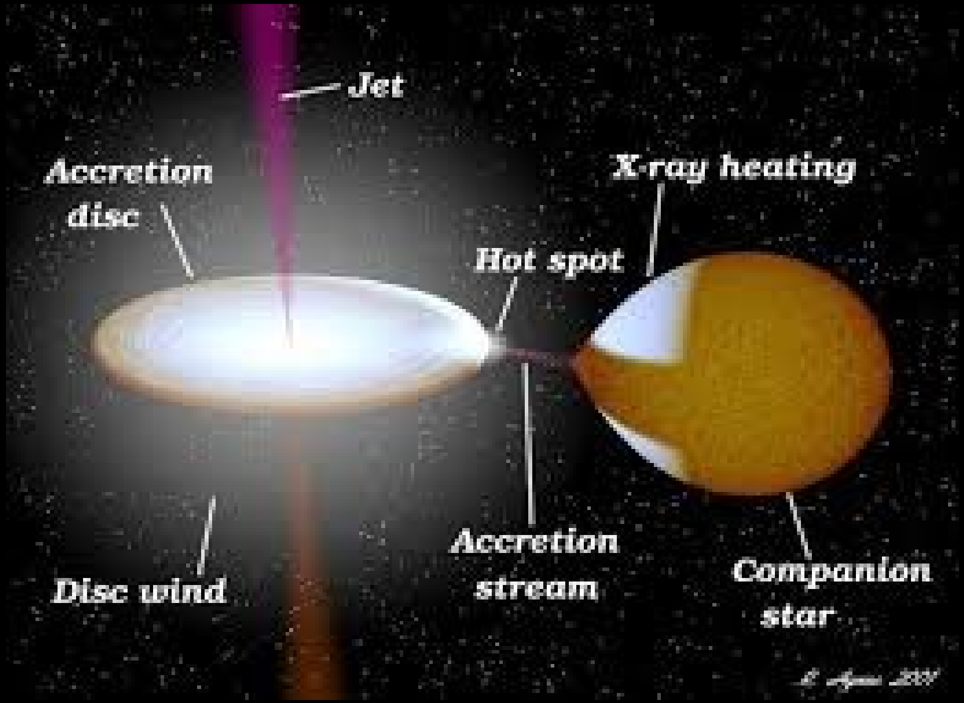
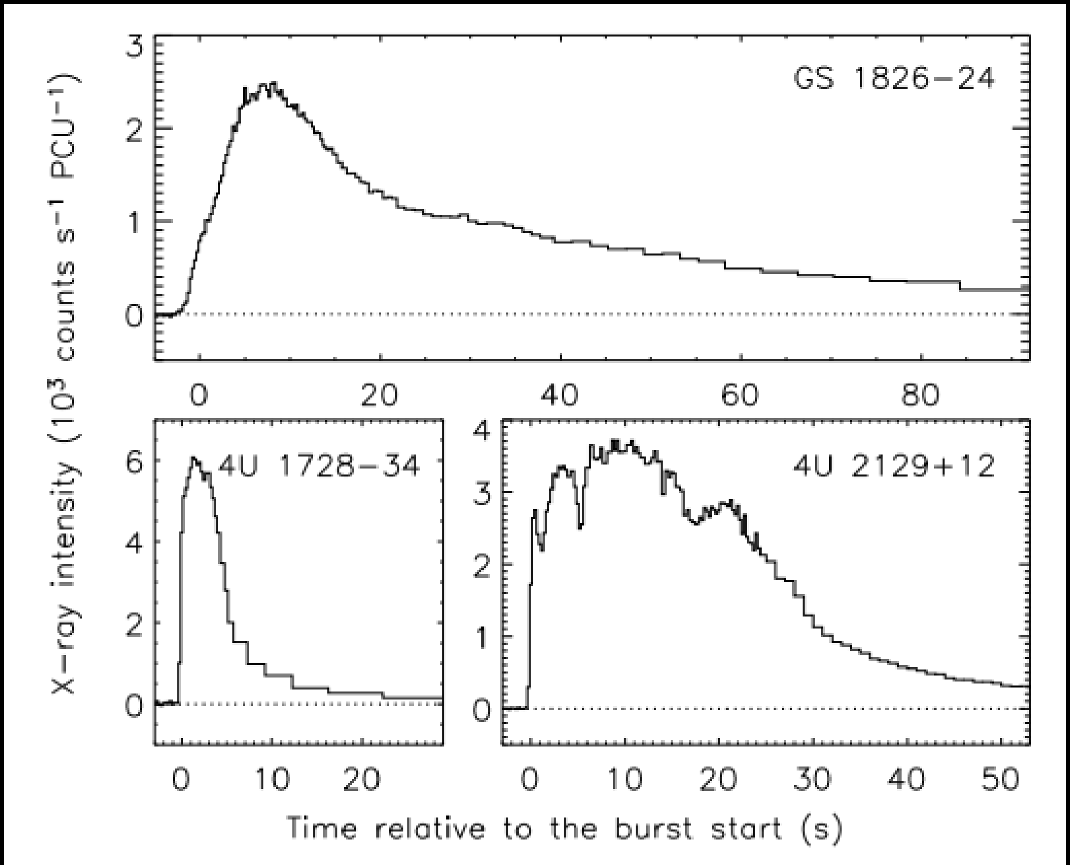


Diagram of an accreting millisecond pulsar.

Source:http://www.redorbit.com/education/reference_library/universe/xray_bia ries/257 /index.html

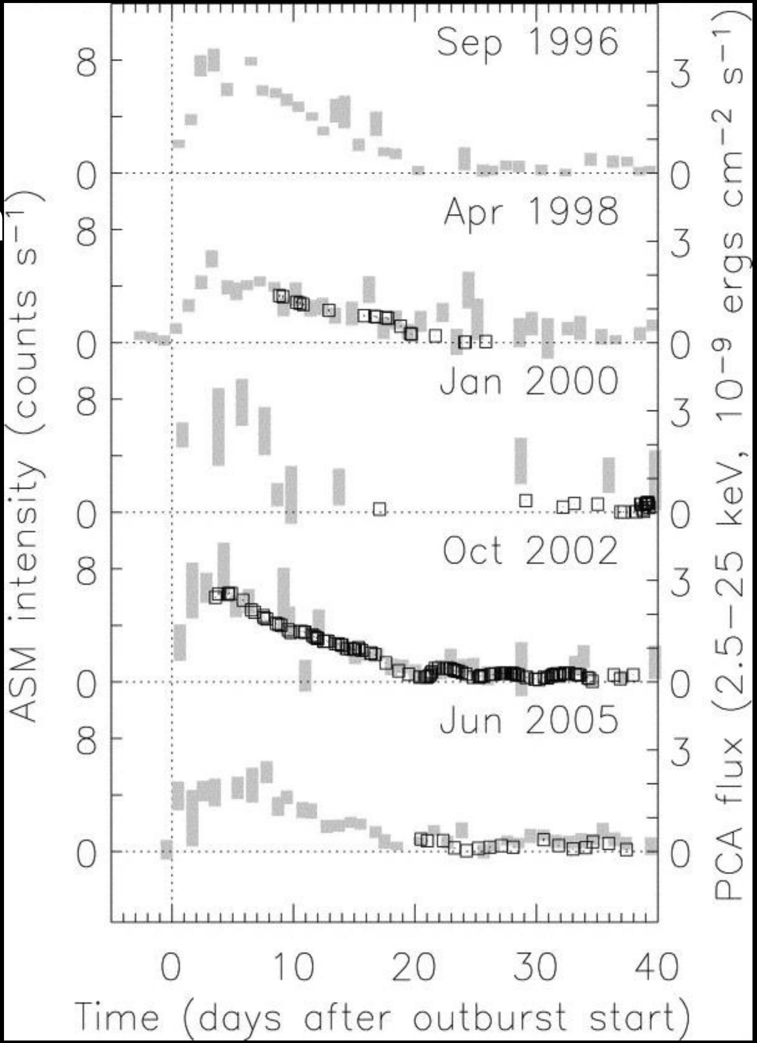
Type I Thermonuclear X-Ray Bursts

- Periodic, rapid increases in the X-Ray luminosity of an accreting neutron star
- Energies of the order of 10^{39} ergs
- Caused by unstable ignition of accreted Hydrogen/Helium on the surface of the neutron star



Example light curves of bursts observed by RXTE

Source: Galloway et al (2008)

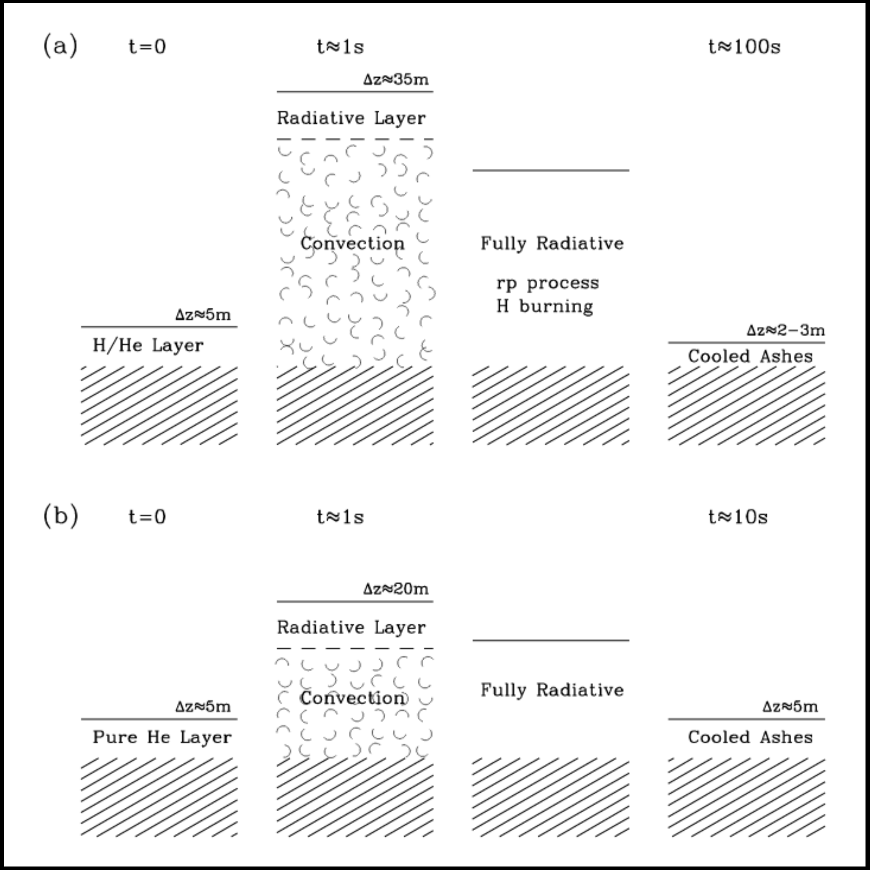


RXTE ASM and PCA X-ray flux measurements throughout the five outbursts of SAX J1808.4-3658

Source: Galloway and Cumming (2006)

SAX J1808.4 – 3658: A Pure He Burster

- Frequent burster (~ every 2.5 years)
- Exhibits **pure helium** thermonuclear bursts: very uncommon in catalogue of known bursters (~5% of sources in MINBAR)



Evolution of the atmosphere during a burst for (a) mixed H/He ignition and (b) pure He ignition

Source: Cumming & Bildsten (2000)

Pure helium bursts:

- Produced by unstable helium burning in a layer of pure helium underlying a stable hydrogen burning shell
- Recurrence time ~1 day, which gives sufficient time for the hot CNO cycle to exhaust accreted hydrogen, causing ignition in a pure helium environment
- Shorter burst duration (~10s) for pure He than for mixed H/He bursts(~30s)

Models of Thermonuclear X-Ray Bursts

Settle Model

- Thermonuclear ignition model
- Developed by Andrew Cumming (see Cumming & Bildsten, 2000)
- Temperature profile of H and He is calculated given an accretion rate and the accumulating layer is allowed to build up until the condition for a thermal runaway is satisfied.
- H assumed to burn via **hot CNO cycle**
- Thickness of accumulating layer determines recurrence time of bursts
- Burst energy calculated by assuming complete burning of the H/He layer
- Accreted material assumed to cover the whole surface of the neutron star.

TABLE 2
PLANE PARALLEL IGNITION CONDITIONS[a]

$\dot{m}/\dot{m}_{Edd}$ [b]	Z_{CNO}	T (10^8 K)	y (10^8 g cm^{-2})	X	Y	ρ (10^6 g cm^{-3})	$y/\dot{m}$ [c] (h)	Δz(90%)[d] (m)
Pure He Ignition								
0.01	0.005	1.49	5.40	0.0	0.995	2.28	170	4.2
	0.01	1.35	12.9	0.0	0.99	4.14	407	5.1
	0.02	1.22	34.0	0.0	0.98	8.01	1073	6.9
0.015	0.01	1.56	3.67	0.0	0.99	1.75	77	3.8
	0.02	1.41	8.50	0.0	0.98	3.11	179	4.4
0.02	0.01	1.74	1.92	0.0	0.99	1.12	30	3.8
	0.02	1.57	3.62	0.0	0.98	1.74	57	3.5
0.03	0.02	1.83	1.56	0.0	0.98	0.97	16	3.6
Mixed H/He Ignition								
0.015	0.005	1.73	2.05	0.01	0.99	1.16	43	4.2
0.02	0.005	1.78	2.18	0.15	0.85	1.04	34	4.5
0.03	0.005	1.86	2.35	0.31	0.69	0.94	25	4.9
	0.01	1.89	1.67	0.14	0.85	0.87	18	4.2
0.1	0.005	2.05	2.70	0.57	0.42	0.84	8.5	5.6
	0.01	2.13	2.04	0.50	0.49	0.71	6.4	5.1
	0.02	2.20	1.51	0.40	0.58	0.62	4.8	4.7
0.3	0.005	2.24	2.62	0.67	0.33	0.76	2.8	5.8
	0.01	2.33	2.14	0.64	0.35	0.66	2.3	5.5
	0.02	2.44	1.70	0.59	0.39	0.57	1.8	5.2

[a] Conditions at the base of the accumulated column at ignition. We take $M = 1.4 M_\odot$, $R = 10$ km, and $g = GM/R^2 = 1.9 \times 10^{14}$ cm s^{-2}. The ignition pressure is $P = gy = 1.9 y_8 \times 10^{22}$ erg cm^{-3} and the accumulated mass over the whole surface is $\Delta M = 4\pi R^2 y = 1.3 y_8 \times 10^{21}$ g. We take the flux from deeper in the star to be $F_b = 150$ keV per nucleon.

[b] $\dot{m}_{Edd} = 8.8 \times 10^4$ g cm^{-2} s^{-1}, equivalent to a global rate $\dot{M}_{Edd} = 1.7 \times 10^{-8} M_\odot$ yr^{-1}.

[c] The time to accumulate the unstable column.

[d] The height above the base which contains 90% of the mass.

Source: Cumming & Bildsten (2000)

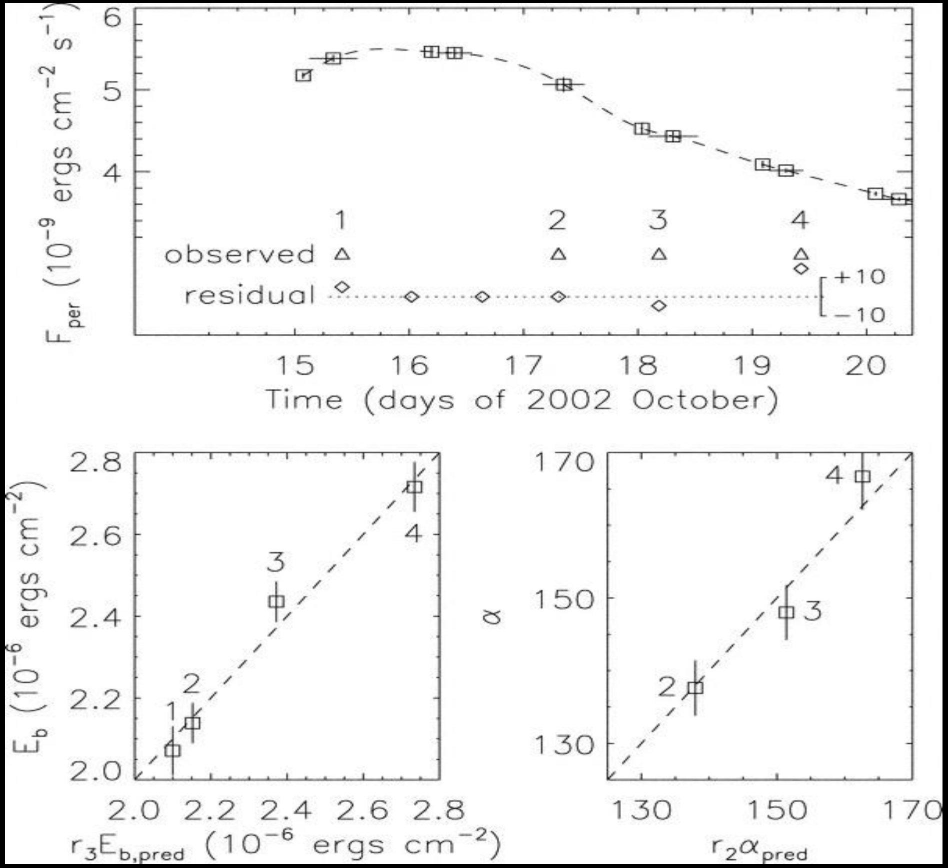
- **Inputs**: Accretion rate, base flux, Hydrogen fraction, metallicity
- **Outputs**: Recurrence time, fluence, alpha, average H fraction... and other things

Our Method

- Match Rossi-X-Ray Timing Explorer observations with a numerical ignition model
- Determine best-fit parameters of the system
    - Distance/inclination
    - Accretion rate
    - Hydrogen fraction/metallicity
- Markov Chain Monte Carlo (MCMC) approach

We use a Python implementation of MCMC called “emcee” see http://dan.iel.fm/emcee/current/ or Foreman-Mackey et al (2013) for details

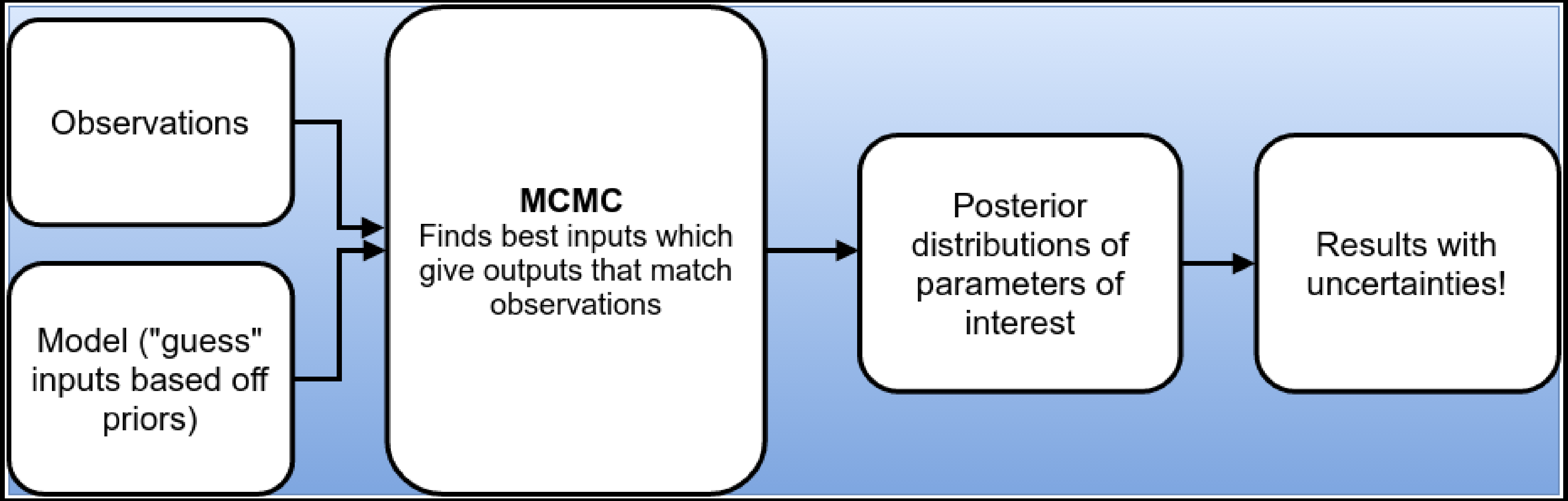
- Based off Galloway & Cumming (2006) analysis, but with improved:
    - Parameter space exploration
    - Updated telescope calibrations
    - Correct treatment of inclination



Galloway et al (2006): Comparison of model results and observed burst properties for SAX J1808.4-3658

Matching Observations with Models using MCMC

MCMC: Markov Chain Monte Carlo



The Likelihood Function:

- Gaussian Likelihood

$$L(x_i \mid \theta, \text{model}) = \frac{1}{\sigma_i f_i \sqrt{2\pi}} \exp\left[\frac{-(x_i - model)^2}{2 f_i \sigma_i^2}\right]$$

- Overall likelihood is multiplication of individual likelihoods for each parameter

Parameters of interest

Non-Observables:

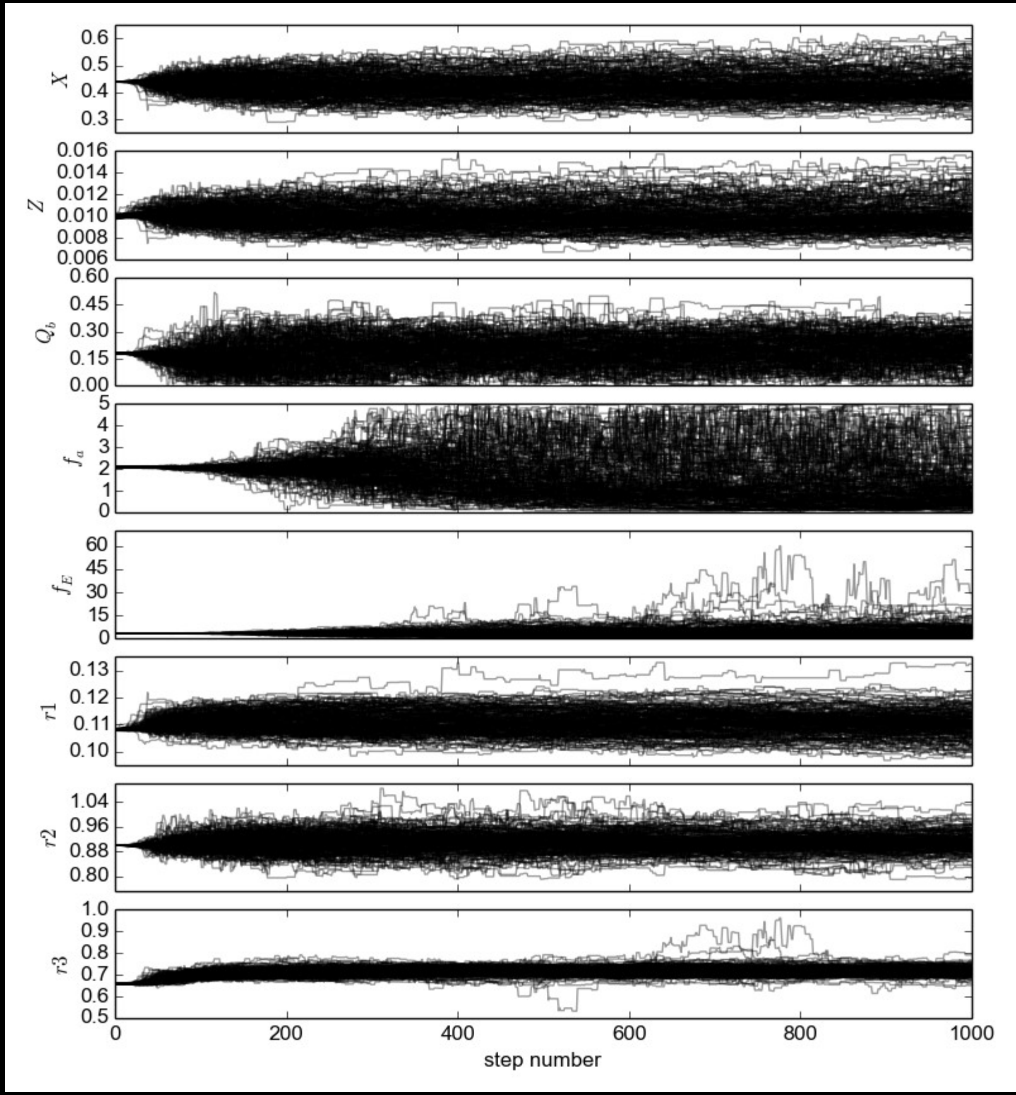
- Hydrogen fraction
- Accretion Rate
- Distance/inclination
- Metallicity
- Base flux
- Mass of Neutron Star
- Radius of Neutron Star
- Beaming Fraction
- “Missed bursts”

Observables:

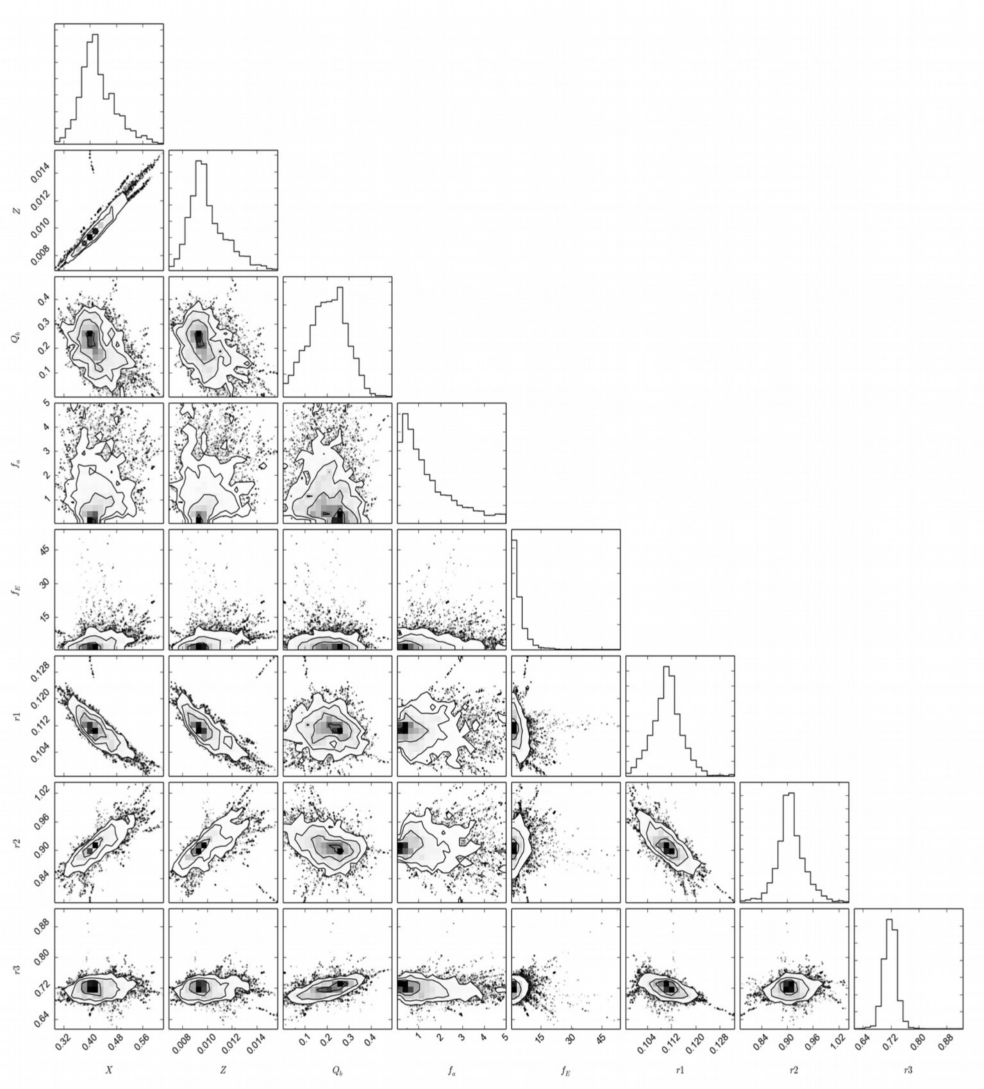
- Fluence
- Recurrence time
- Alpha (ratio of nuclear burning energy to gravitational energy)

Results

- MCMC output



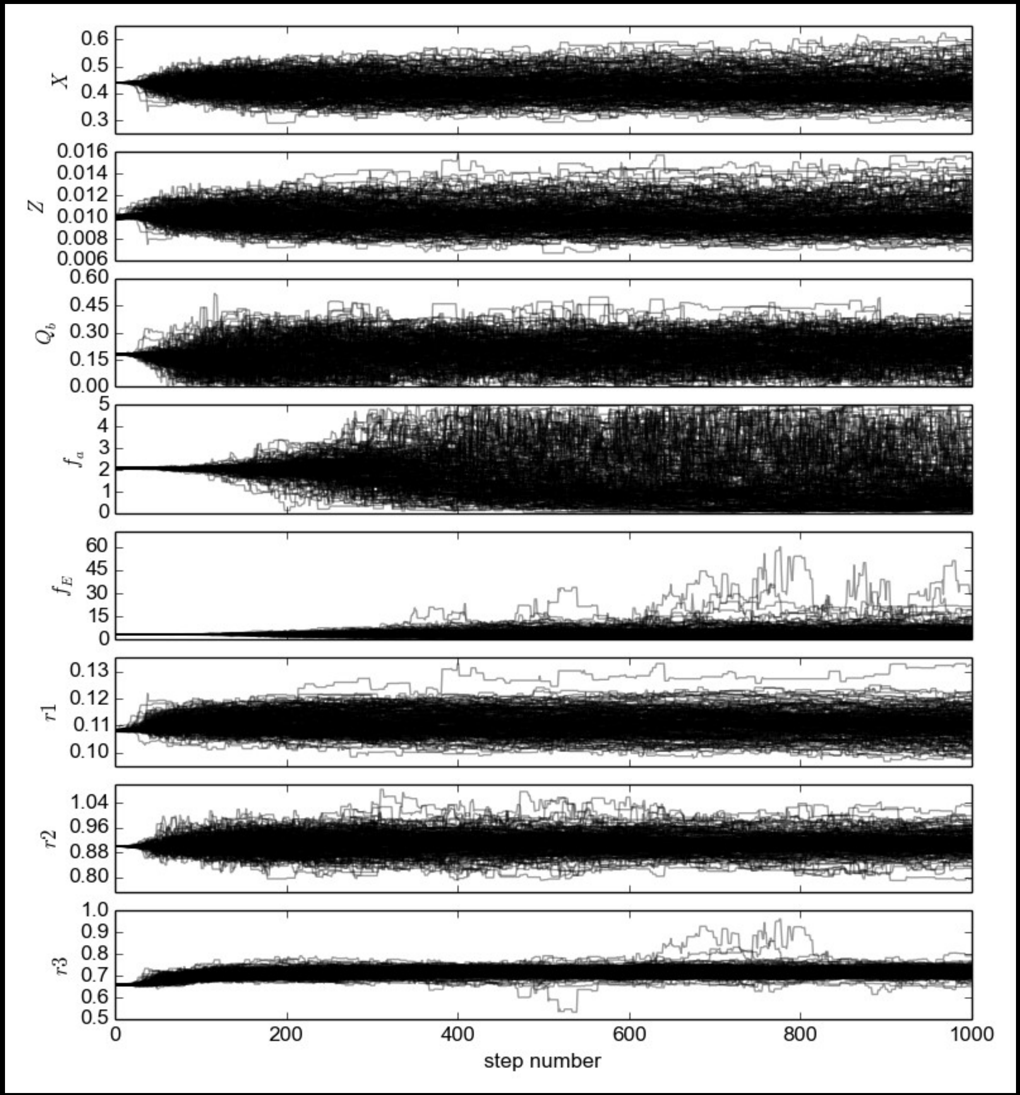
Example chains output from MCMC



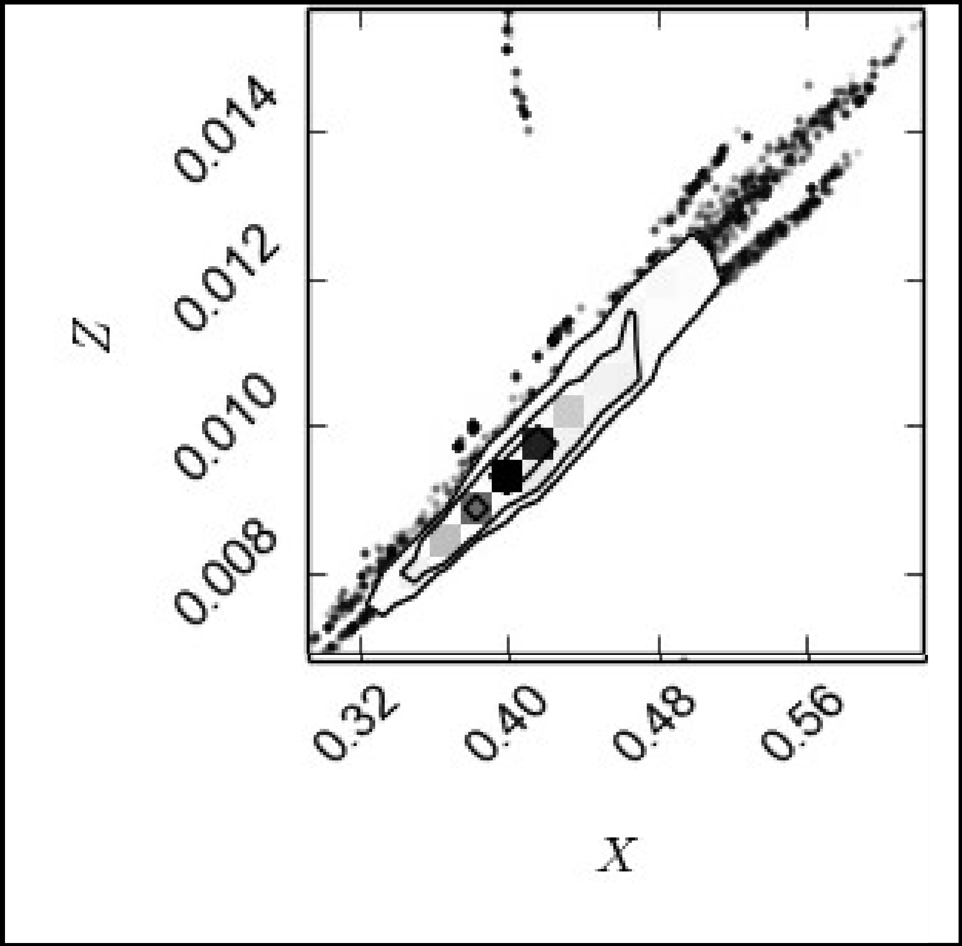
Example parameter distributions, showing confidence regions

Results

- MCMC chain output and triangle plots



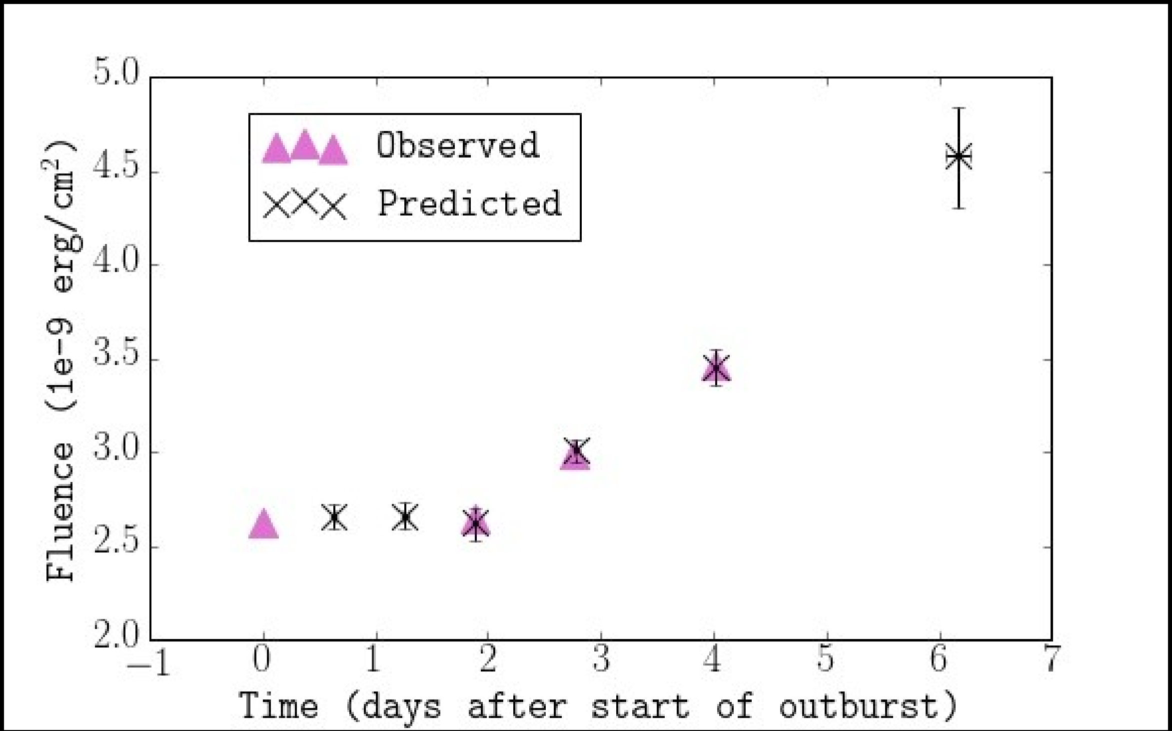
Example chains output from MCMC



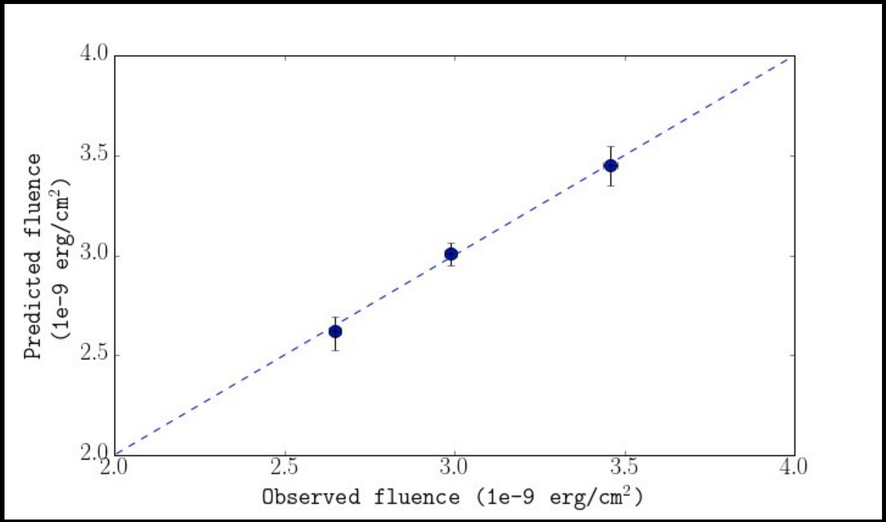
X (H fraction) vs Z (metallicity) confidence regions

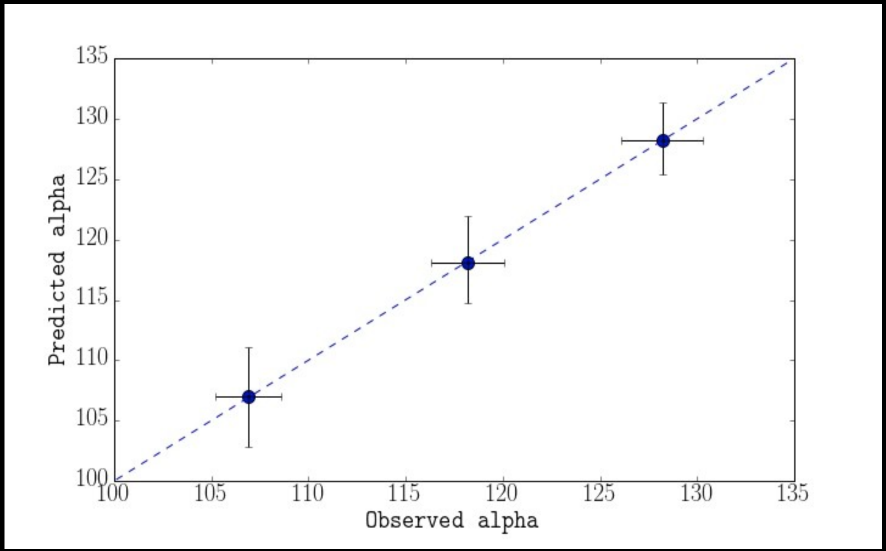
SAX J1808.4-3568: Results

- We predict 3 extra bursts that were not observed



RMS error of burst times: 0.005 days





SAX J1808.4-3568: Results

- Distance/inclination:

  3.48 – 3.53 kpc

  (compared to lower limit of 3.4 kpc from Galloway & Cumming (2006))

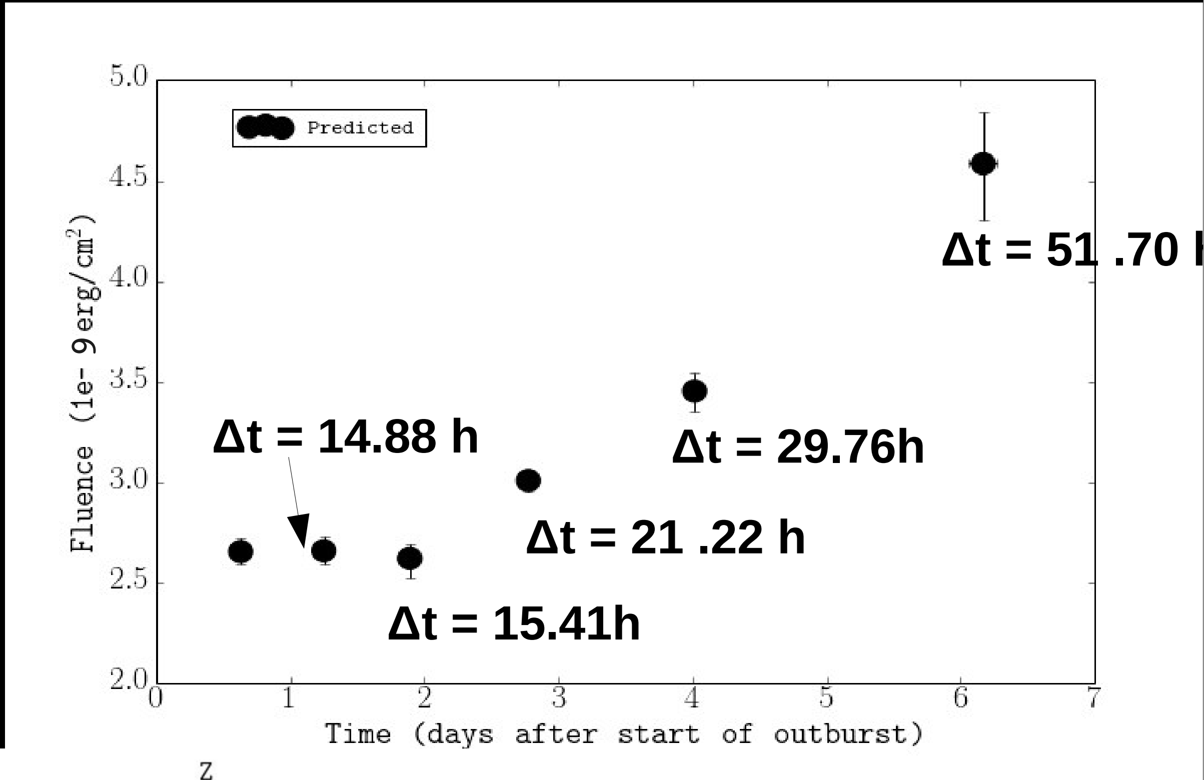
- Hydrogen fraction:

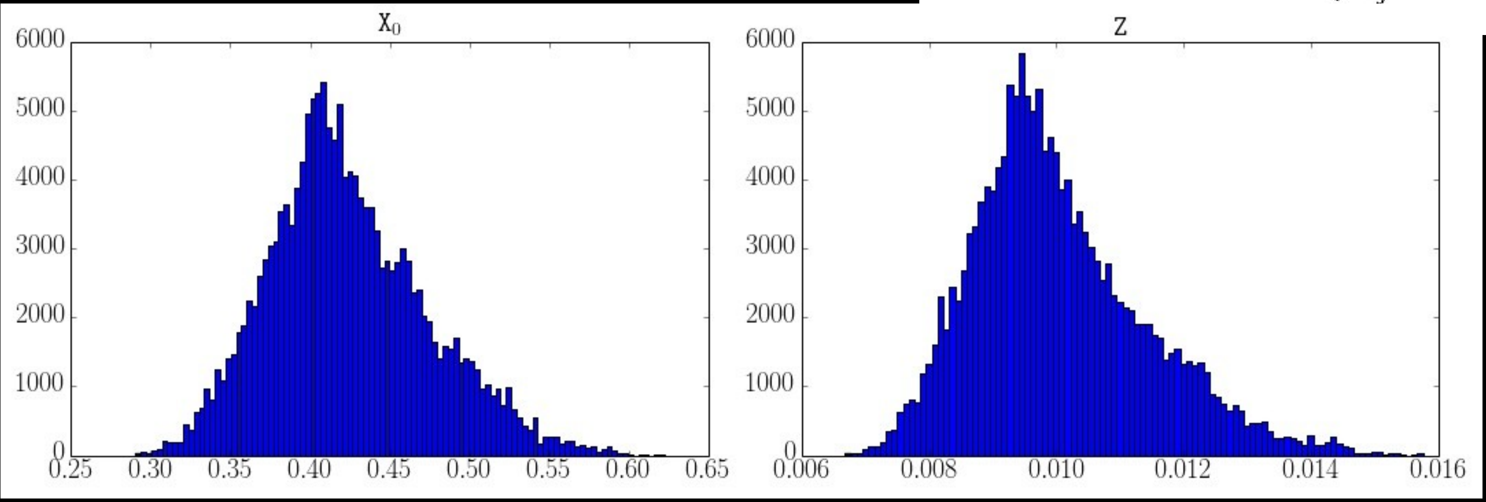
  0.40 ± 0.01

- Metallicity:

  0.0093 ± 0.0004

- Burst Recurrence time (hours):





Posterior distributions of Hydrogen fraction (X_0) and metallicity (Z)

Summary

- We have developed a method to match observations of accretion powered millisecond pulsars with models to determine non-observable parameters of the system
- This enables us to constrain parameters such as fuel composition and distance, that aids in understanding the mechanisms behind thermonuclear X-Ray bursts, as well as testing current models
- We are developing a catalogue of standard cases to be used as a reference for modelling studies

Any Questions? Email me: adelle.goodwin@monash.edu