HMXB X-RAY PULSARS IN THE MAGELLANIC CLOUDS AND THE GALAXY: THE SMC CORE PROGRAM

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RXTE'S ADVANTAGES FOR HMXBS

- RXTE was a superb tool for studying high-mass X-ray binaries in our Galaxy.
  - ASM for long term light-curves and detection of transients.
    - e.g. Orbital periods from light curves.
  - PCA for shorter time variability.
    - e.g. Pulse periods and pulse timing.
  - HEXTE for extended energy coverage
    - e.g. cyclotron lines

HMXB STUDIES BEYOND THE MILKY WAY

- In addition to RXTE's highly-productive observations of Galactic systems, RXTE was able to use its unique capabilities to "exit" the Milky Way.

- This presentation briefly reviews highlights from RXTE's extended observations of the Small Magellanic Cloud that became part of the "core program" until mission end.

- Includes the discovery of a huge population of HMXBs.

- SMC statistics: dwarf galaxy; *possibly* in orbit around the Milky Way; d ~ 60 kpc; mass ~1% MW; low metallicity; recent bursts of increased star formation rate - due to tidal interactions with LMC and/or MW(?).

EARLY HISTORY OF SMC X-RAY PULSARS: SMC X-1, X-2, X-3.

- First X-ray pulsar discovered in SMC was SMC X-1 in 1970s.
- Luminosity can reach ~10^{39} ergs s^{-1}.
- 0.71s pulse period, 3.89 day orbital period.
- Companion is Roche-lobe filling B0I star.
- In 1978 two transients (SMC X-2, X-3) found.
- Three pulsars found agreed with simple population prediction based on SMC mass (1% of Milky Way)

EARLY OBSERVATIONS OF SMC X-RAY PULSARS WITH RXTE

- Serendipitous RXTE PCA slew observations in 1997 showed possible outburst from SMC X-3 (Marshall+).

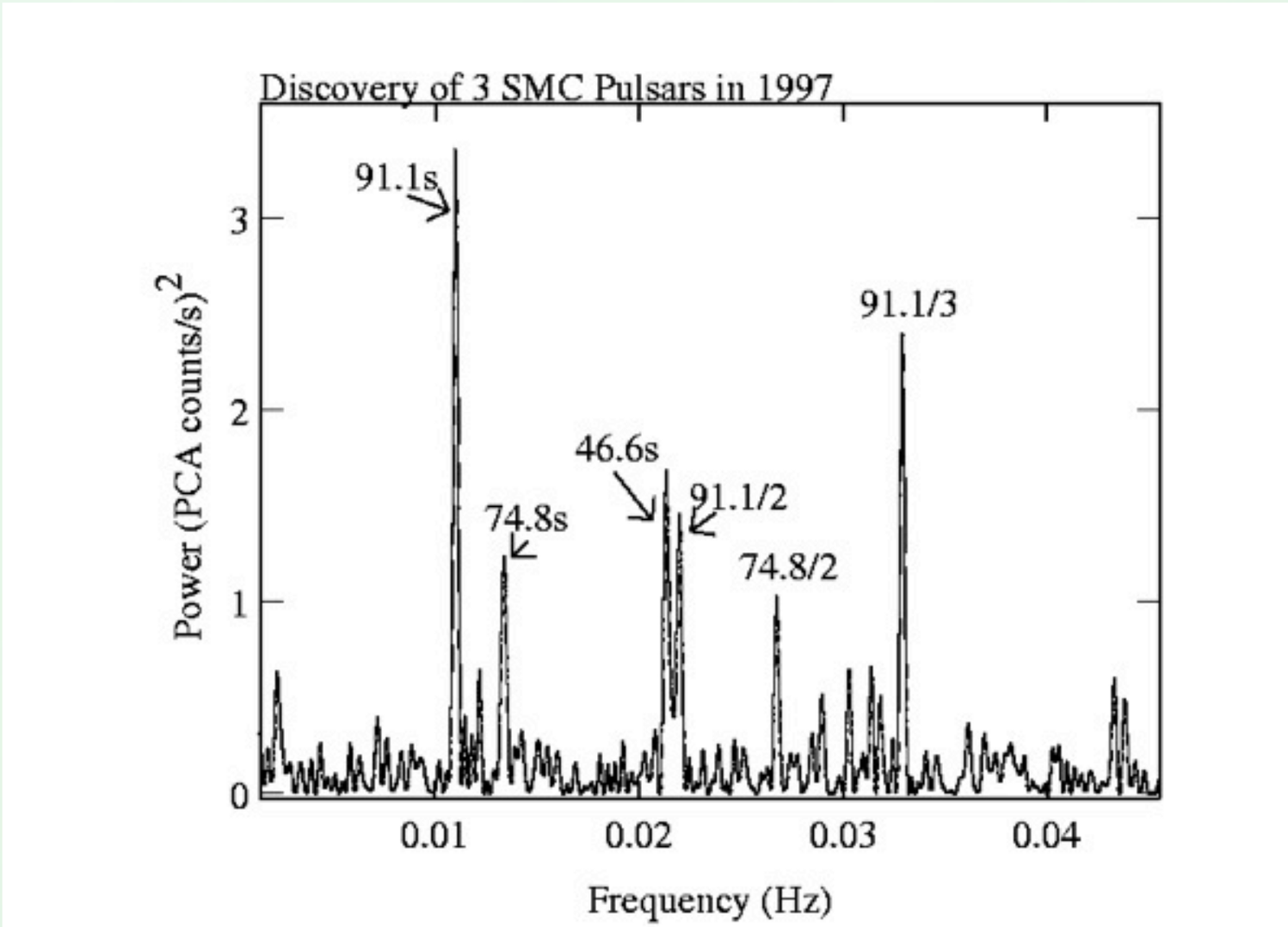
- Pointed RXTE observation showed complicated power spectrum with several (harmonic, almost-harmonic, & non-harmonic) peaks.

- Imaging ASCA satellite observations (Corbet+) showed two separate pulsars - neither was SMC X-3...

- Examined the PCA power spectrum in more detail...

THE POWER SPECTRUM THAT STARTED IT ALL!

Revised investigation of RXTE power spectrum (Corbet+) showed three pulsars simultaneously active!
(Periods of 46.6, 91.1, and 74.8 s).



THE SMC WITH RXTE

- Monitored one or more positions weekly since 1997.
- Typical observation duration about 10,000 seconds.
- Became one of the RXTE "core programs".
- Use power spectrum of light curve to extract pulsed flux from any X-ray pulsars in FOV.
- Sensitivity to pulsed flux ~10^{36} ergs s^{-1} at SMC distance.
- Detect transient sources - *all identified optical counterparts are Be stars*.
- There are now more than 60 SMC HMXBs known.

Accretion From a Be Star

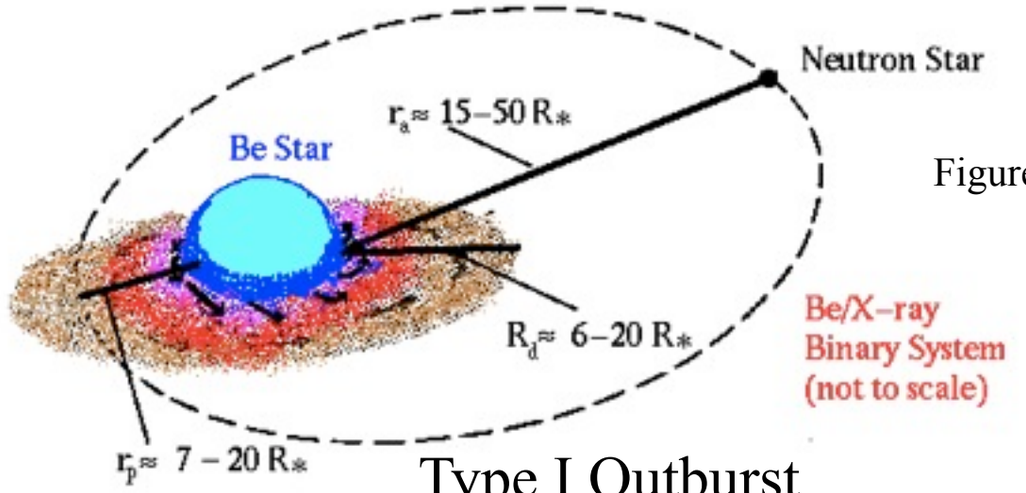
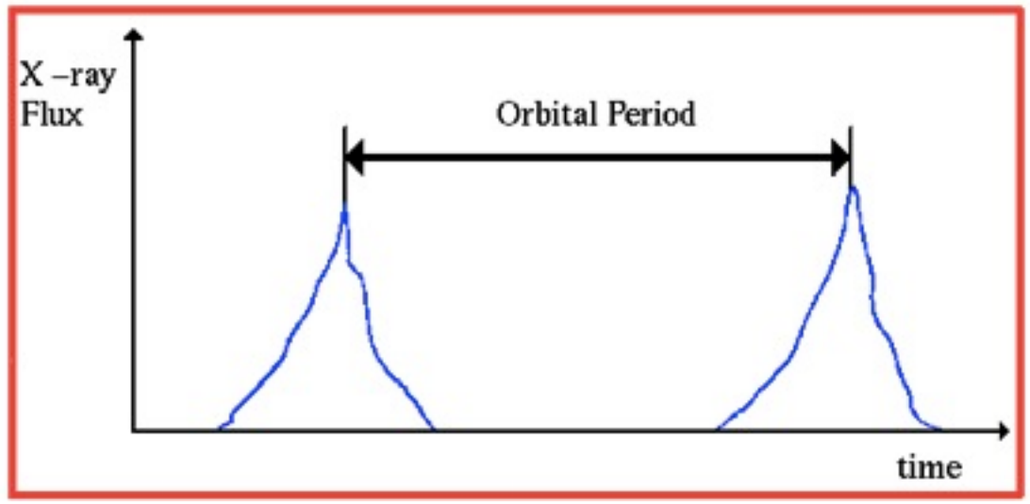


Figure from Ignacio Negueruela

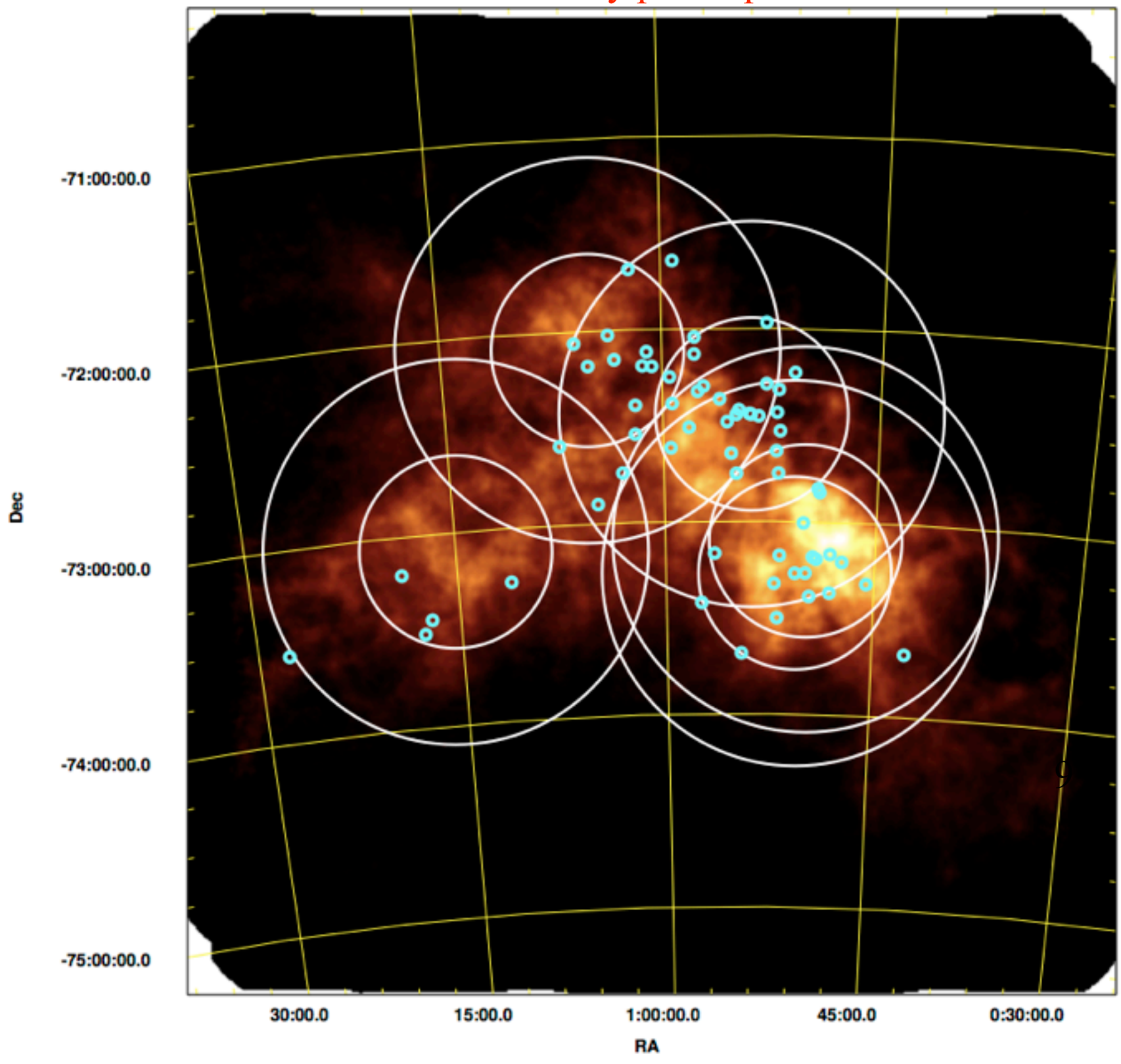
Type I Outburst



In addition to periodic modulation on orbital period, systems are also transient on long timescales as Be circumstellar envelope dissipates and reforms.

HI Image of the SMC. Big circles = PCA FOV at monitoring positions.

Small blue circles show X-ray pulsar positions.



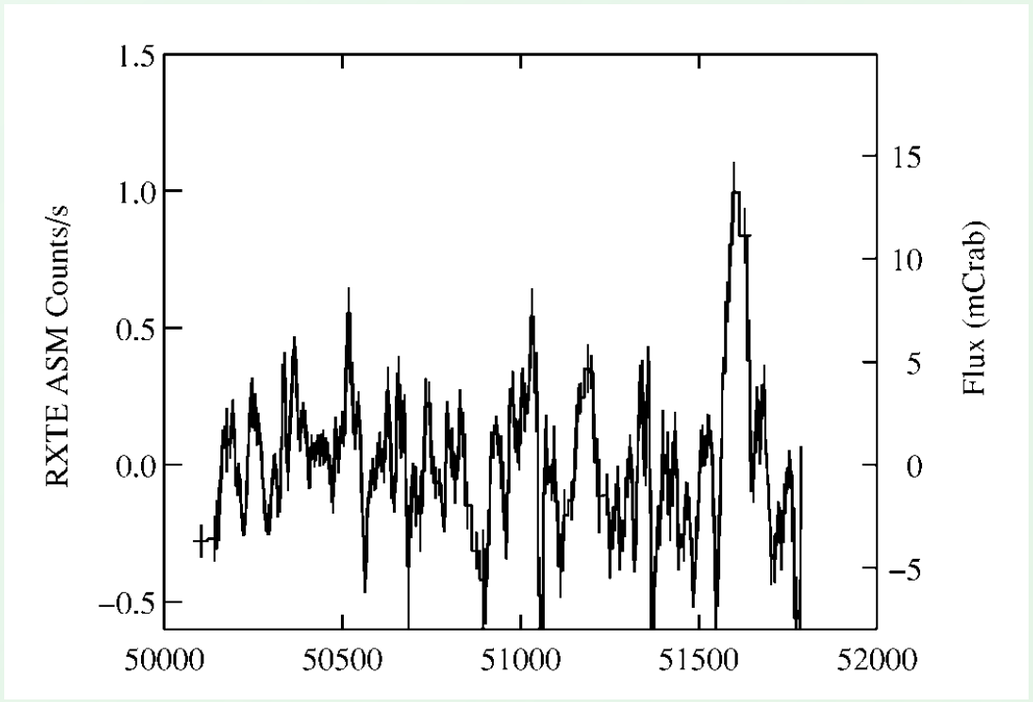
SELECTED HIGHLIGHTS OF SMC OBSERVATIONS

- Outbursts from SMC X-2 (Corbet+, Schurch+)
- Long-term pulsed light curves (Galache+, Laycock+, Townsend)
- Orbital parameters of SMC binaries (Townsend+)
- Accretion theory with XRBs in the SMC (Coe+)
- Spectral class distribution of Be/X-ray binaries (McBride+)
- Two populations of X-ray pulsars produced by two types of supernova (Knigge+)

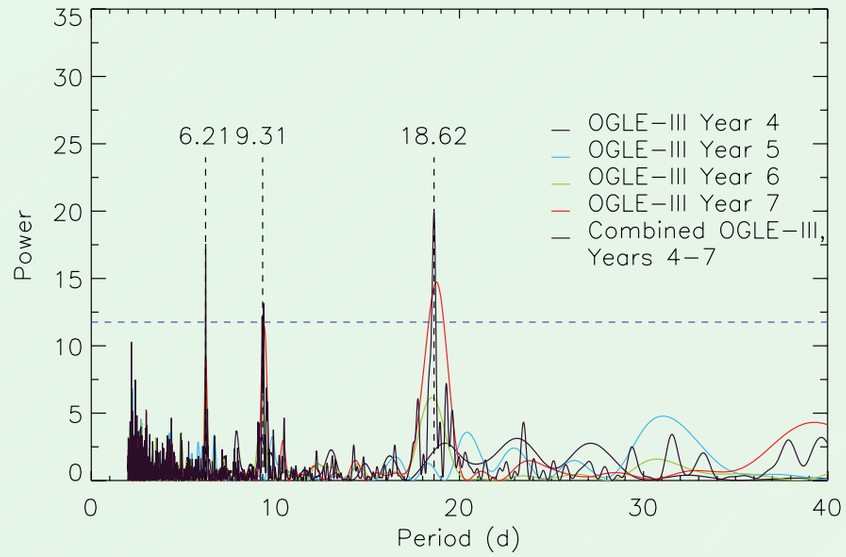
OUTBURST AND PULSED X-RAY FLUX FROM SMC X-2 - AND OGLE

SMC X-2 - one of the 3 "classical" HMXBs in the SMC.

Outburst seen with the ASM > 10^{38} ergs s^{-1}
Exceptional to detect SMC Be system with ASM)



Triggered PCA TOO - 2.37s period pulsations found (Corbet+).
Short pulse period consistent with high L_x.



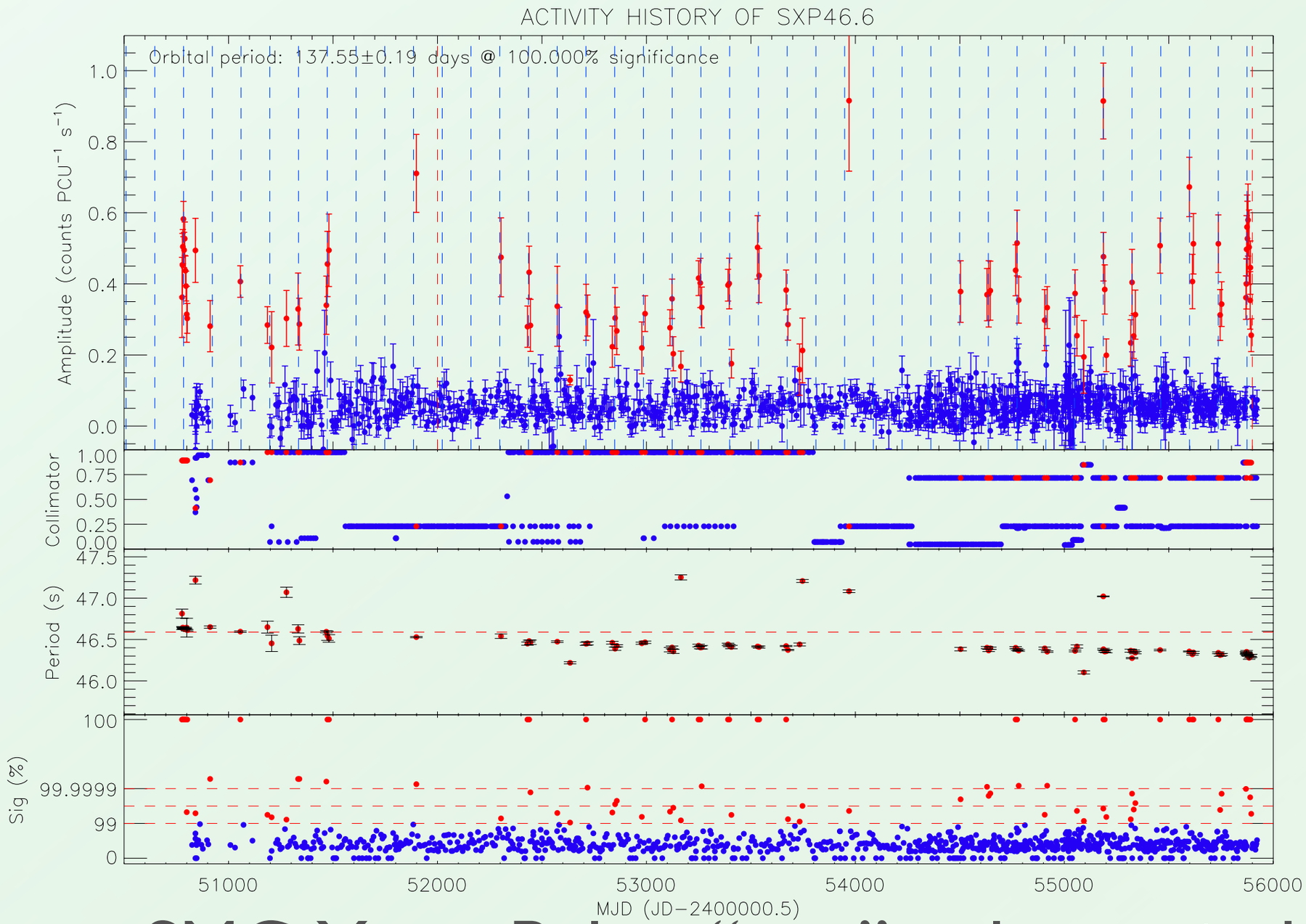
Orbital period not seen in X-ray data (PCA or ASM).

OGLE monitoring of optical counterpart over 4 year period shows 18.6 day period (Schurch+).

LONG-TERM PULSAR LIGHT CURVES

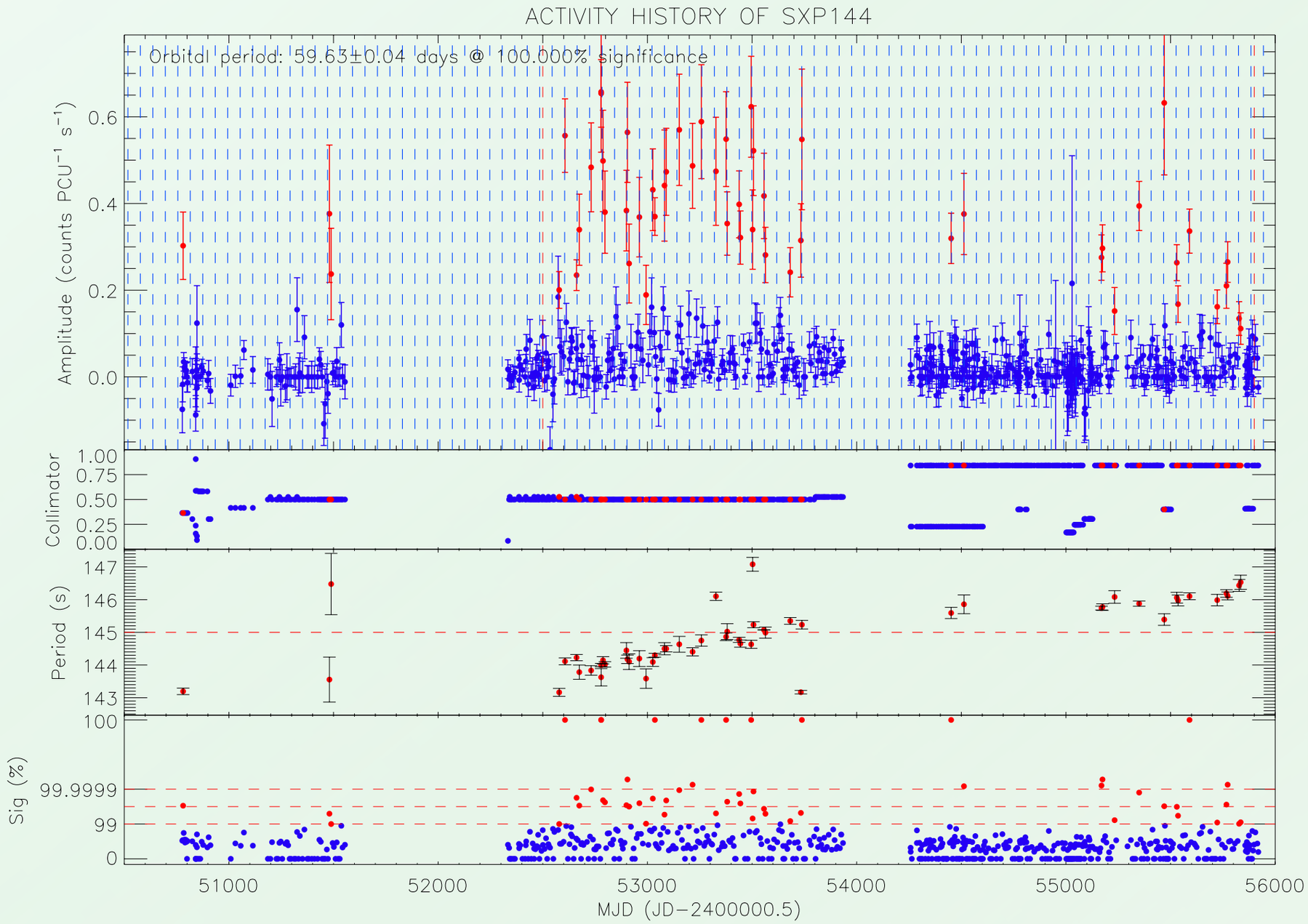
- Light curves are extracted for each SMC observation.
- Power spectra are calculated for each light curve.
- Measure the pulsed flux (or upper limits) for each known pulsar in the FOV.
  - While RXTE was operational, used quick look data to do this within ~1 day as a weather report. Check for new sources or new outbursts from known sources. (~15 ATels)
- Obtain long-term pulsed light curves. 2 large papers written, so far, with light curves for all sources (Laycock+, Galache+). Light curves further updated in Townsend PhD thesis.

EXAMPLE LIGHT CURVES

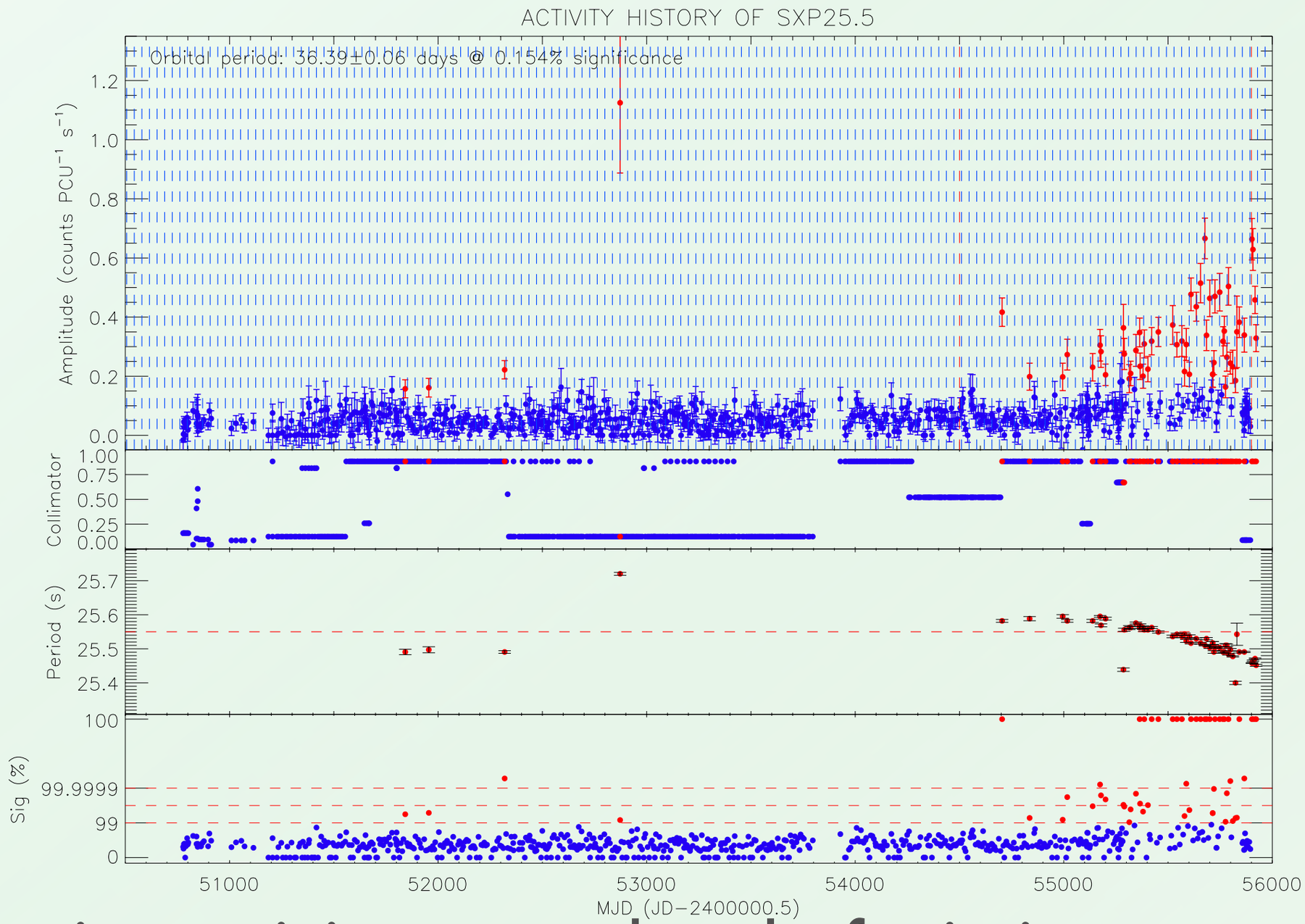


SXPnnn = SMC X-ray Pulsar "nnn" pulse period.
e.g. "SXP46.6" (one of first new pulsars).
137 day orbital modulation seen.

SXP144: 59 day orbital period.



SXP25.5 (perhaps = SXP51!)

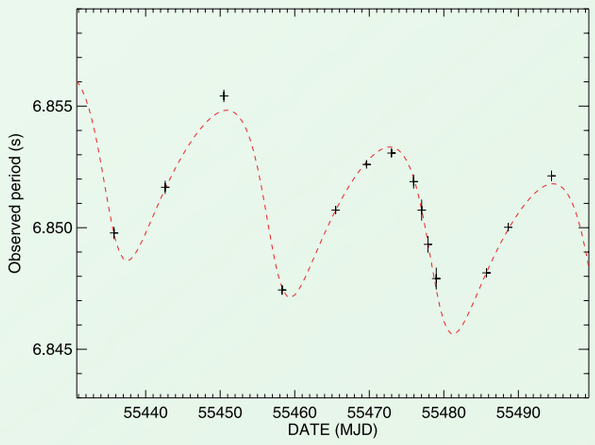


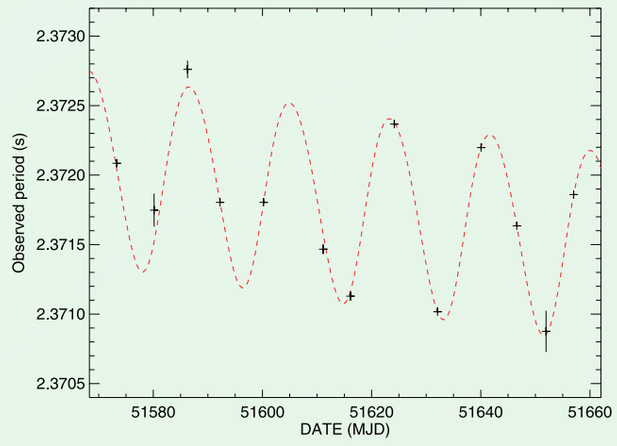
Increasing activity toward end of mission.

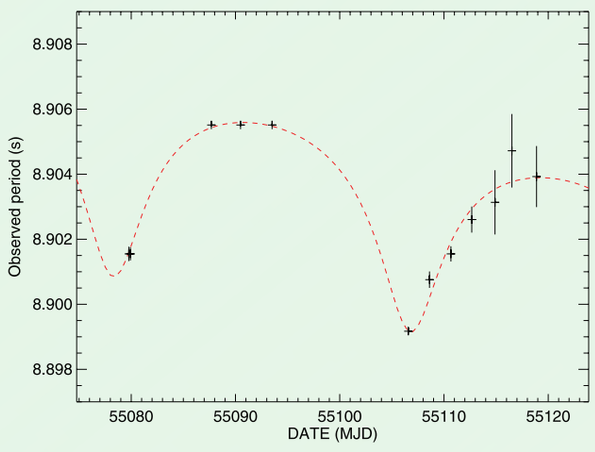
Power spectrum sometimes shows 25.5s only, sometimes 51s. Changing pulse profile or two sources??

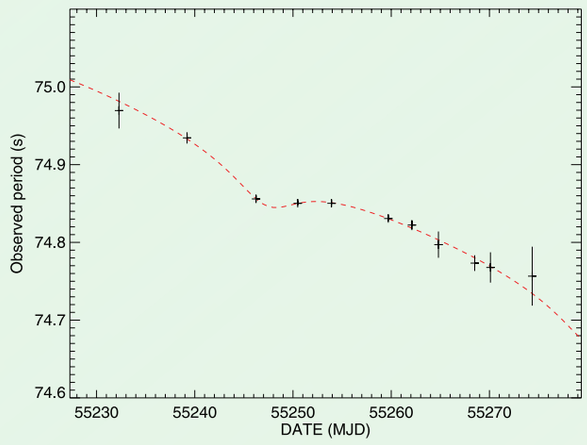
ORBITAL PARAMETERS OF SMC BINARIES (TOWNSEND+)

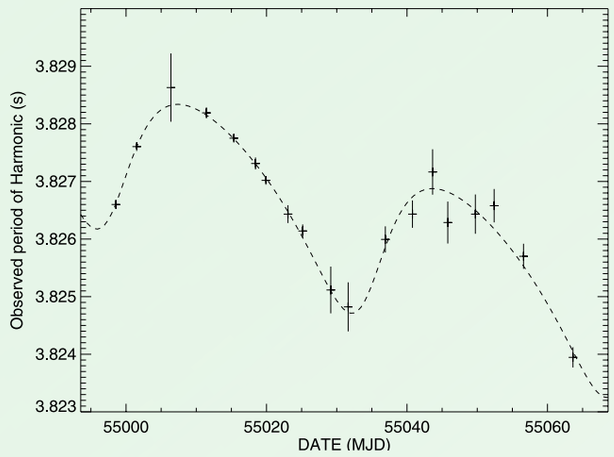
Extended Type II outburst allowed repeated TOO observations which enabled measurements of orbital parameters from pulse timing.



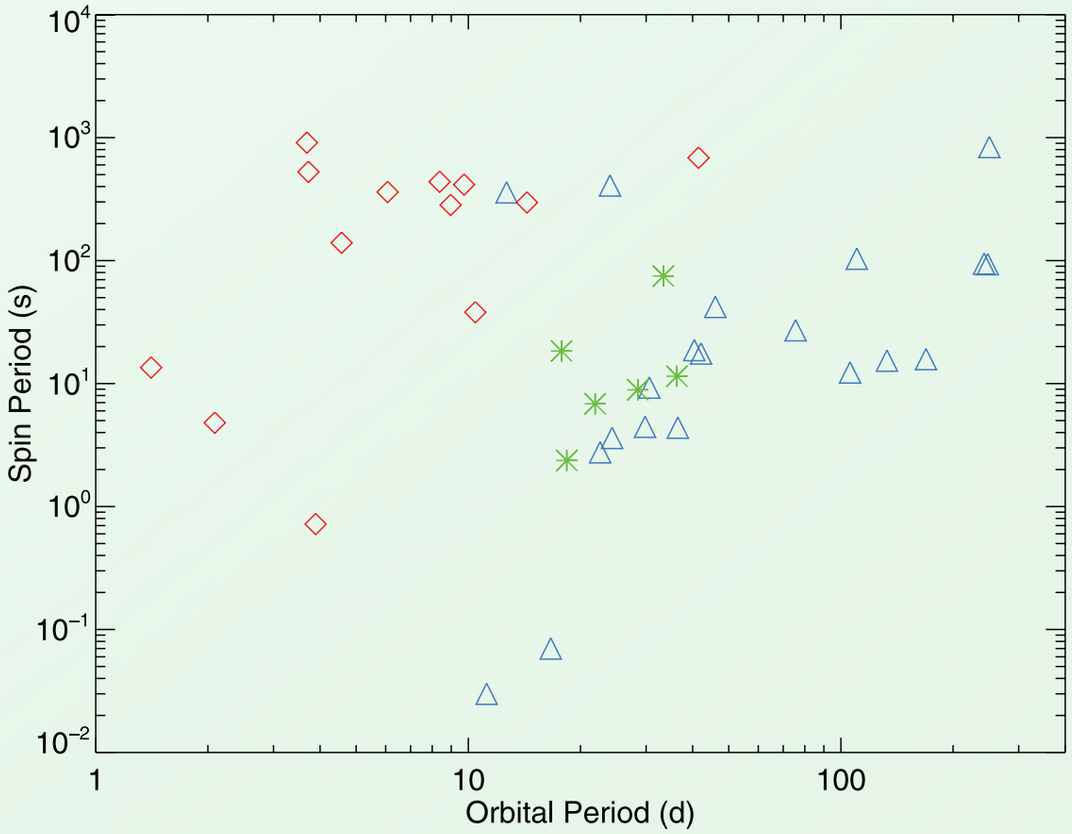


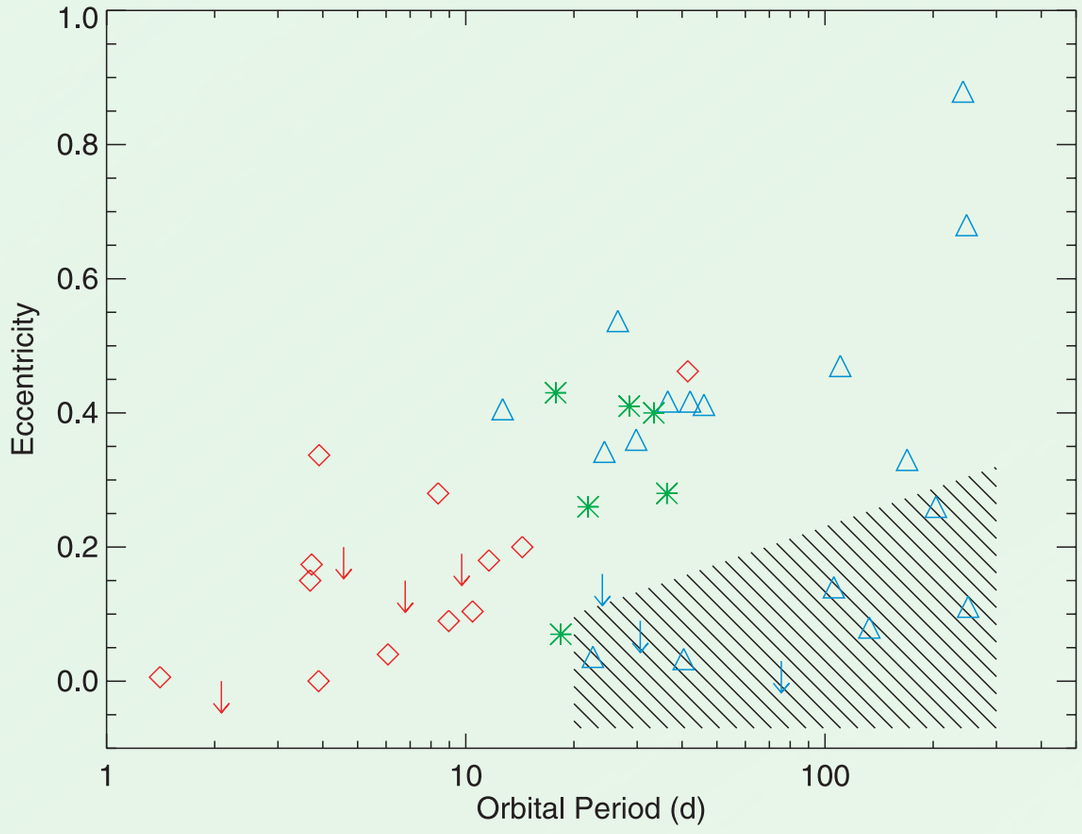






ORBITAL PERIOD/ECCENTRICITY CORRELATION?





ACCRETION THEORY WITH X-RAY BINARIES IN THE SMC (COE+)

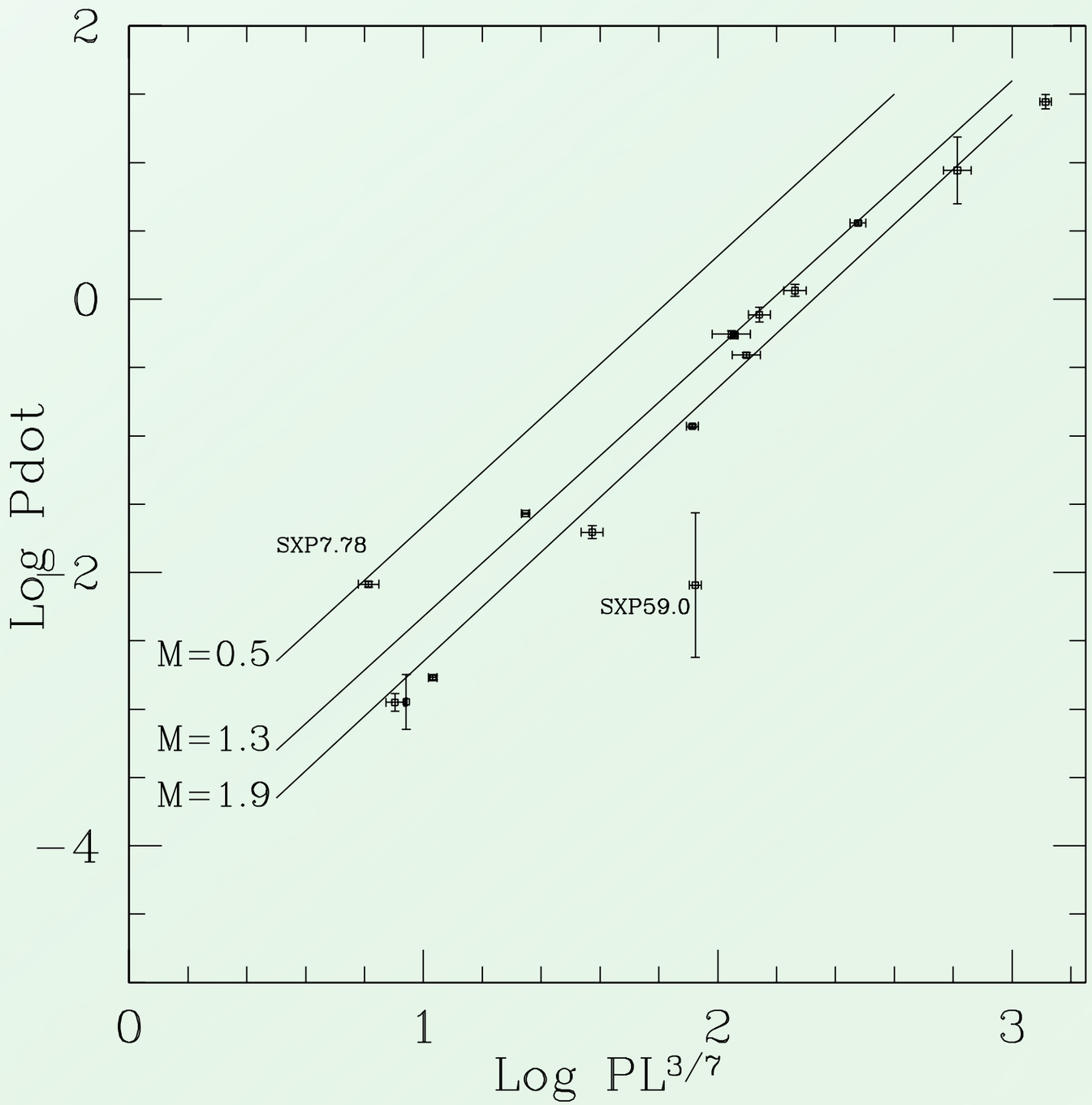
- Understanding of the accretion process on to compact objects in binary systems is an important part of modern astrophysics.

- Theoretical work (Ghosh & Lamb) makes clear predictions for the behavior of such systems.

    - Generally supported by observational results of considerably varying quality from galactic accreting pulsar systems.

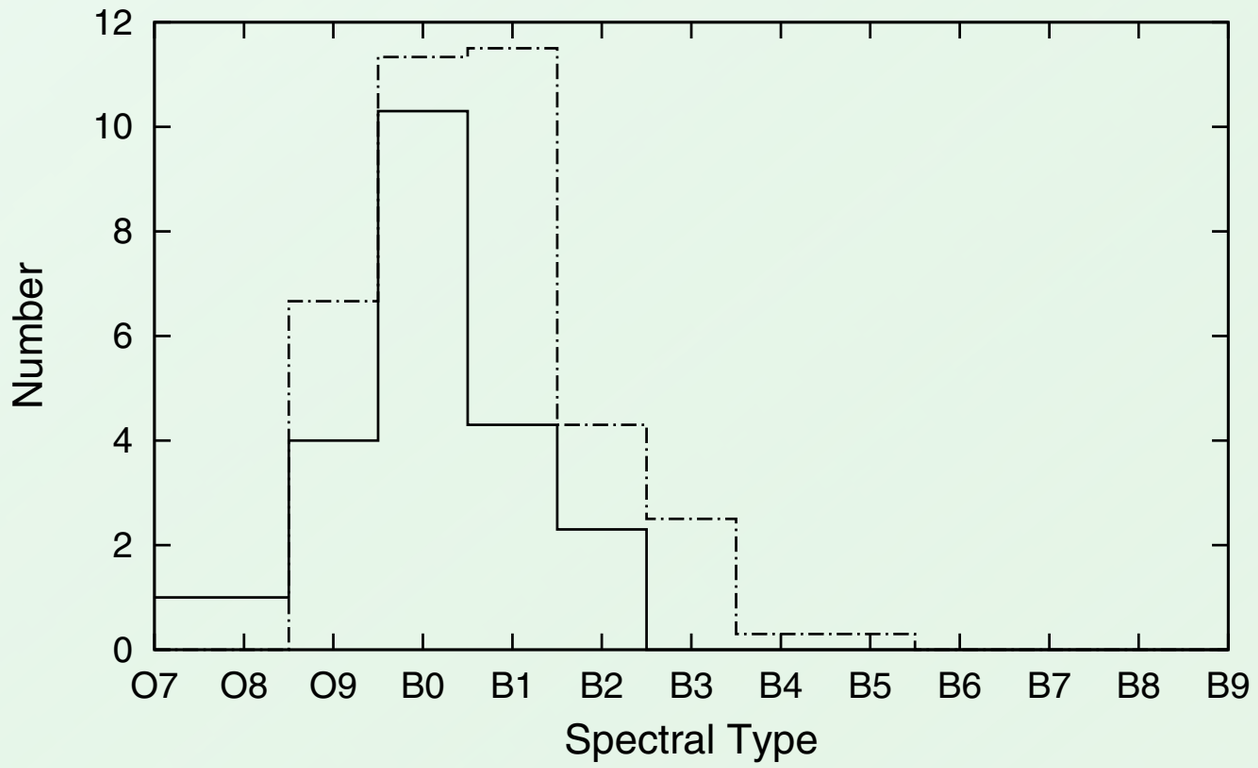
- A much larger homogeneous SMC population provides more demanding tests of the accretion theory.

ACCRETION THEORY FROM SMC X-RAY BINARIES



Adapted from fig. 10 of Ghosh & Lamb (1979) for disc accretion on to neutron stars with a magnetic moment of μ = 0.48. All 16 outbursts with a measurable dP/dt from Table 1 are included. The three parallel lines represent three different possible neutron star masses.

SPECTRAL CLASS DISTRIBUTION OF BE/X-RAY BINARIES (MCBRIDE+)



The spectral distribution of Be/X-ray binaries in the SMC is consistent with that of the Galaxy, despite the lower metallicity of the SMC.

The metallicity of the SMC is conducive to the formation of a large number of high-mass X-ray binaries.

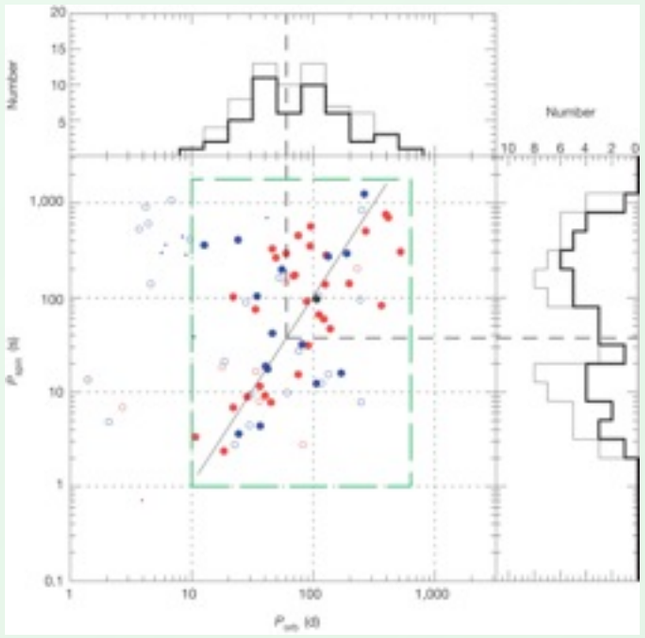
However, the spectral distribution is likely most strongly influenced by angular momentum losses during binary evolution. This is not very dependent on the local metallicity.

TWO POPULATIONS OF X-RAY PULSARS PRODUCED BY TWO TYPES OF SUPERNOVA (KNIGGE+)

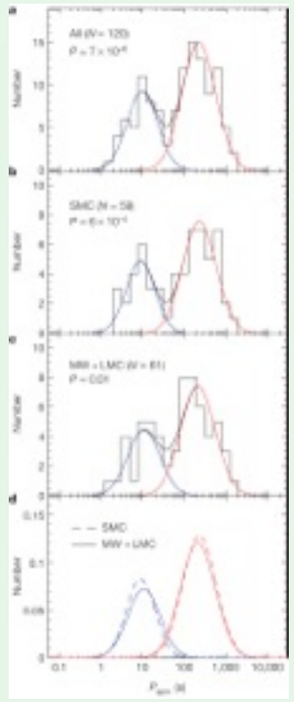
- Two types of supernova are thought to produce neutron stars.
  - Iron-core-collapse supernovae: a high-mass star develops a degenerate iron core exceeding the Chandrasekhar limit.
  - Electron-capture supernovae: collapse of a lower-mass oxygen–neon–magnesium core.
- Knigge et al. (2012) report that X-ray pulsars are composed of two distinct subpopulations with different characteristic

TWO POPULATIONS OF X-RAY PULSARS

The Corbet diagram for high-mass X-ray binaries.



The log(P_{spin}) distribution of confirmed and probable BeXs.



C Knigge *et al*. *Nature* **000**, 1-4 (2011) doi:10.1038/nature10529

Knigge et al.: "The two subpopulations are most probably associated with the two distinct types of neutron-star-forming supernova, with electron-capture supernovae preferentially producing systems with short spin periods, short orbital periods and low eccentricities. Intriguingly, the split between the two subpopulations is clearest in the distribution of the logarithm of spin period, a result that had not been predicted and which still remains to be explained."

nature

SOME METRICS OF PRODUCTIVITY OF SMC CORE PROGRAM

- Over 80 publications of all types.
- Over 20 refereed papers, with more in the pipeline.
- 4 PhD theses (Laycock, Galache, Schurch, Townsend)
- An extensive legacy of data and results available for observational and theoretical studies. (e.g. Knigge et al. Nature paper)