Superorbital Modulation in the X-ray Binary 4U 1538-52 with the BAT and GBM

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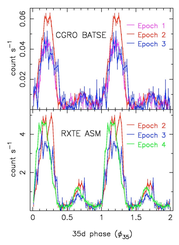
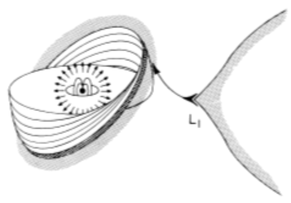
Superorbital periods in Roche-lobe overflowing X-ray binaries such as Her X-1 have been known for some time. These can be understood as being related to the presence of an accretion disk. However, more recently a number of HMXBs accreting from the wind of their supergiant companion, where the presence of a persistent accretion disk is unlikely, have also been found to show superorbital modulation. Swift BAT observations now reveal superorbital modulation in the wind-accreting supergiant high-mass X-ray binary (HMXB) 4U 1538-52 at a period of 14.9130 +/- 0.0026 days that is consistent with four times the 3.73 day orbital period. These periods agree with a previously suggested correlation between superorbital and orbital periods in similar HMXBs. During the ~14 years of observations the superorbital modulation changes amplitude, and since ~MJD 57,650 it was no longer detected in the power spectrum, although a peak near the second harmonic of this was present for some time. Measurements of the spin period of the neutron star in the system with the Fermi Gamma-ray Burst Monitor show a long-term spin-down trend which halted towards the end of the light curve, suggesting a connection between dP(spin)/dt and superorbital modulation, as proposed for 2S 0114+650. However, an earlier torque reversal from INTEGRAL observations was not associated with superorbital modulation changes. B and V band photometry from the Las Cumbres Observatory reveals orbital ellipsoidal photometric variability, but no superorbital optical modulation. However the photometry was obtained when the 14.9130 day period was no longer detected in the BAT power spectrum. We consider superorbital modulation mechanisms, and suggest that the Corotating Interaction Region model, with small deviations from orbital synchronization, appears promising. Since the start of 2020 (MJD ~58,850), 4U 1538-52 has been exhibiting a spin-up trend and we have been monitoring the system to determine whether the superorbital modulation has reappeared.

Superorbital Periods in HMXBs

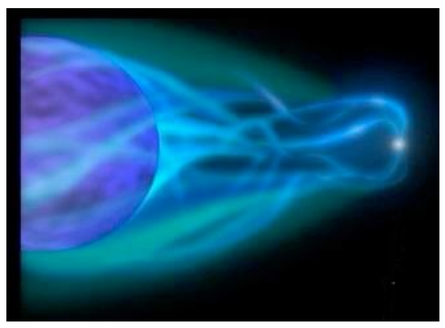
- **Superorbital periods are well-known in systems like Her X-1 (35 days), SMC X-1 (~55 days), LMC X-4 (~30.5 days)**
- **Primary stars in these systems ~fill their Roche-lobes.**
- **Modulation possibly caused by precessing accretion disk - radiation induced warping?**





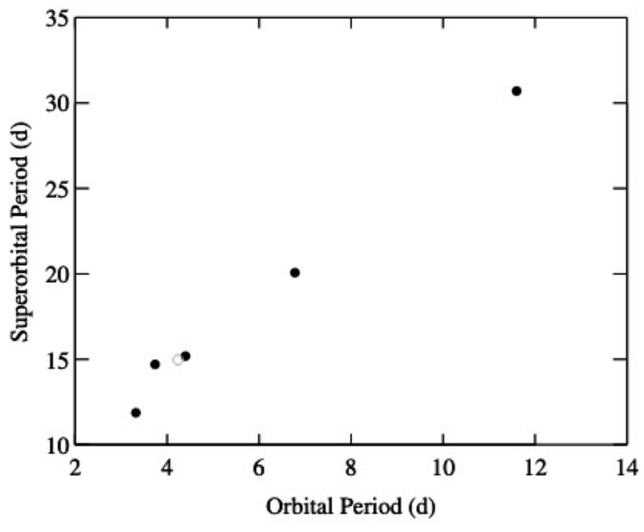
Superorbital Modulation in Wind Accretors

- **Superorbital periods more recently found in five systems that accrete from stellar wind:**
  - **2S 0114+650 (Farrell+ 2006), IGR J16493-4348, IGR J16418-4543, IGR J16479-4514, 4U 1909+07 (Corbet & Krimm 2013).**
- **Don't expect to have an accretion disk (not enough angular momentum). Disk precession models don't work.**
- **It was puzzling what could cause superorbital periods in these systems.**



(ESA)

Correlation of Superorbital & Orbital Periods?

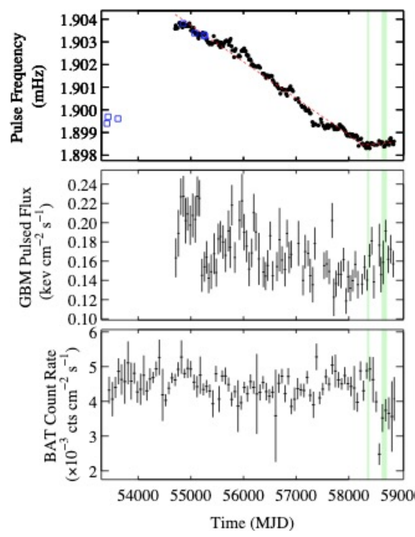


- **Possible correlation between superorbital period and orbital period.**
- **Various models proposed: 3 body systems, stellar pulsations, wind structure.**
- **Unclear how any mechanism could give such a correlation.**

The HMXB 4U 1538-52

- **Fairly bright (~20 mCrab) high-mass X-ray binary**
- **Long known, and well studied**
- **~526 s pulse period (neutron star rotation)**
- **Eclipsing, 3.73 day orbital period**
- **Eccentricity unclear with various values reported. 0.0?**
- **Accretes from wind of B0 Iab companion QV Nor**
- **QV Nor shows "ellipsoidal" photometric modulation or period (tidal distortion)**

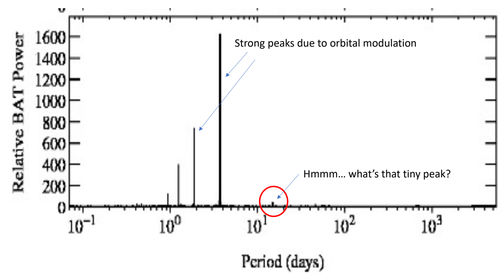
Long Term X-ray Observations



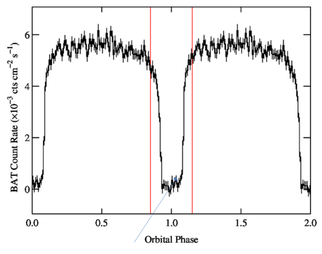
Pulse Frequency (Fermi GBM)

Pulsed Flux (GBM)

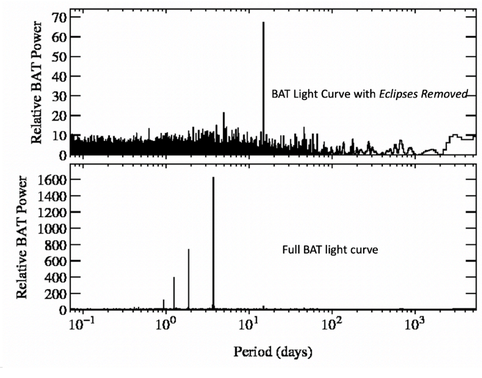
Flux (Swift BAT)



BAT Light Curve Folded on Orbital Period

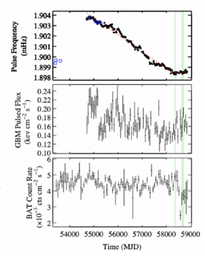


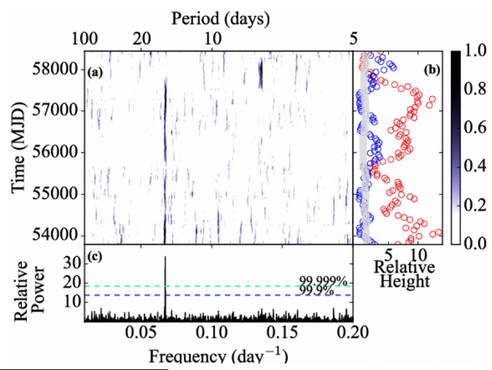
Remove data from times in eclipse...

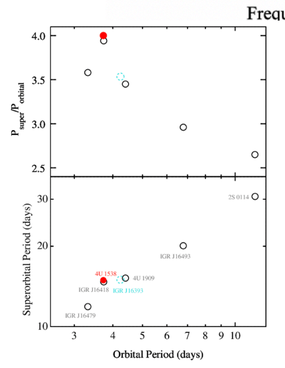


Superorbital & $\dot{P}_{spin}$ Connection?

Long-term Behavior of Superorbital Modulation



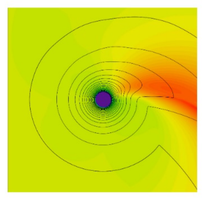




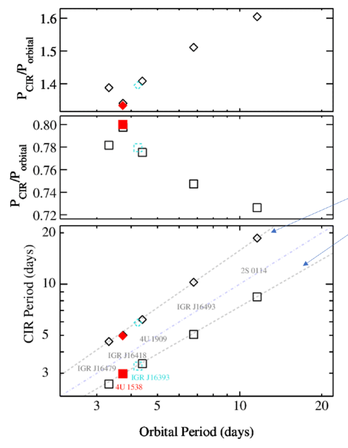
4U 1538 (and IGR 16393) consistent with proposed correlation between orbital period and superorbital period.

Only 4U 1538 shows an integer ratio between orbital and superorbital periods. (IGR J16418 is slightly different.)

Superorbital Models - CIRs



- ***Corotating Interaction Region* model (Bozzo+ 2017).**
- **Structure in wind corotates with primary star.**
- **Superorbital period is the *beat period* between the *orbital* period and *rotation* period as neutron star passes through dense region.**
- ***We can calculate the implied rotation period of the CIR***



There are *two possible CIR periods* depending whether the CIR is rotating
more slowly (♦) or
more quickly (■) than the *orbital frequency*.

For both cases, the CIR period is very highly correlated with the orbital period. r = 0.999

For 4U 1538, the CIR period is either 4/5 or 4/3 x orbital period.

Maybe the CIR period is "synchronized-*ish*"

Why Imperfect Orbital Synchronization?

- **Eccentric orbit**
  - **For an eccentric orbit, synchronization is driven by orbital velocity at *periastron* (Hut 1981, Lurie 2017).**
  - **Could result in CIR rotating faster than orbital frequency**
- **Differential rotation in primary**
  - **CIRs may be tied to star spots not at equator.**
  - **For O4I star ζPup Ramiaramanantsoa et al. (2018) proposed that CIR linked to spots at higher latitudes, rotating faster than equator.**
  - **In late-type stars Kepler observations suggested higher latitudes rotating slower than synchronous.**

Further Studies of Superorbital Phenomenon

- **Superorbital modulation can vary in strength and profile**
- **Connected with changes in spin $\dot{P}$?**
- **Want to monitor neutron star periods in other superorbital systems to determine how spin $\dot{P}$ changes when superorbital modulation changes.**

- ***Superorbital modulation is telling us something important about the primary star, its wind, and accretion properties – we just have to figure out what it is!***