X-Ray Eclipse Time Delays in 4U2129+47

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Active State

1978 --> Discovered with Uhuru, Active State, \( F_x \sim 3 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) (Formann et al. 1978)

1979-1982 --> Optical + X-ray

Accretion Disk Coronae

\( D \sim 6.3 \text{ kpc} \quad P_{\text{orb}} \sim 5.2 \text{ hr} \)

(Thorstensen, 1979; McClintok et al., 1982)
Inactive State  \( F_x \sim 10^{-12} \) --> Spectrum of the Companion Star?

1983 – 1989 --> Flat Light Curve
Spectrum of F IV star

Dynamical Interaction?
Long Term Radial Velocity Shifts
\(~40\,\text{km s}^{-1}\)
--> Orbital period \(~30\,\text{d}\)

Bothwell et al. (2008); Garcia et al., (1989)

2000 --> CHANDRA POSITION: F star and binary coincident to within 0.1''

(Nowak et al., 2002)
Our XMM-Newton Observations

15 May 2005
$T_0 = 2453506.4825(3)$ JD

6 June 2005
$T_0 = 2453528.3061(4)$
The Observed-Calculated residuals technique

\[ \Delta T = T_n - T_{n-pred} \]

FIT with:

\[ \Delta T = \alpha + \beta n + \gamma n^2 \]

\[ T_{\text{ref}} \]

Correction

\[ P_{\text{ref}} \]

Correction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{ref}} ) (JD)</td>
<td>2444403.7443\pm0.0013</td>
</tr>
<tr>
<td>( P_{\text{orb}} ) (s)</td>
<td>18857.594\pm0.007</td>
</tr>
<tr>
<td>( \dot{P}_{\text{orb}} ) (s s(^{-1}))</td>
<td>((1.03\pm0.13)\times10^{-10})</td>
</tr>
<tr>
<td>( P_{\text{orb}}^{-1} ) (yr)</td>
<td>((5.8\pm0.7)\times10^6)</td>
</tr>
<tr>
<td>( \chi^2 / \text{d.o.f.} )</td>
<td>25.6/3</td>
</tr>
</tbody>
</table>

192 ± 43 s
Triple System!

The period of this oscillation is the period of the eclipsing binary around the center of mass of the triple system.
Constraints on the triple system orbital period

Third star ($M_1$)  
C.O.M.  
Eclipsing binary ($M_2$)

radial velocity shifts

$P_\nu (d)$

$M_1 / M_\odot$

1.1  1.3  1.5  1.7

i=90°
Triple System Consequences...

No orbital evolution required

Third Star

Eclipsing Binary
Conclusions

4U2129+47 is (likely) part of a triple system (first system of this kind showing this strong evidence)

But we still need...

- Monthly spaced X-ray observations: sinusoidal modulation triple parameters (Mass, Period, ...)
- Optical observations: radial velocity

  - To reveal the real nature of the orbital period evolution
  - To measure Modulation in the X-ray eclipse times.

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Constraints on the triple system orbital period

Eclipsing binary

Third star

\[ \Delta Z = a \left[ \sin(\varphi + \Delta \varphi) - \sin(\varphi) \right] \]

\[ \Delta \varphi = \varphi_1 - \varphi_2 \approx 22 \text{ d} / P_{\text{orb}} \]

\[ \tau = \Delta Z / c \]
Constraints on the triple system orbital period

\[ Z \]

\[ 1 \leq a_2 \leq 2 \]

\[ P_{\text{orb}} = \frac{1}{v} \]

\[ v_R = \Omega a_1 = 2\pi P_{\text{orb}}^{-1} a_1 < 20 \text{ km s}^{-1} \]
Summary

• 4U2129+47 history from ~1978 to ~2005
  Active State
    Observations
    Accretion disk Coronae Source (ADC)
  Inactive State
    Observations up to 2000
    Interpretations

• Our Lucky XMM-Newton Observations (Inactive State)
  Triple System Evidences
  Constrains on the Triple Object Orbital Period
**INTERPRETATION**

- $F_x \sim 10^{-13}$ erg cm$^{-2}$ s$^{-1}$
- Collapse of the ADC of a factor $\sim 5$
- Thick outer disk rim
- Coincident with the F star to within $0.1''$

**Sharp and total Eclipse:**

$$d = 1523^{+30}_{-50} \text{ s}$$

\[ \text{Inactive State} \]

\[ \text{\textcopyright Nowak et al., 2002} \]
Accretion Disk Coronae (ADC)

Scattered and Observed X-ray Emission

$L_X \sim 10^{36} - 10^{35} \text{ erg s}^{-1}$

Near Edge-On Accreting Binary System

Binary orbital modulation in the light curves

Broad and partial X-ray eclipses

[Graph showing orbital phase versus relative intensity with X-ray emission from 0.1 to 3.7 keV]
Mid-Eclipse Epochs

$T_0 = 2453506.4825(3) \text{ JD}$
(15 May 2007)

$T_0 = 2453528.3061(4)$
(6 June 2005)
Conclusions: Spectral Analysis

Short Observations --> few photons --> No detailed spectra obtained ...

...mystery on the QUIESCENT EMISSION of 4U2129+47 is still unveiled...

Low statistic, no sinusoidal modulation observed
Active State: OBSERVATIONS

1978 --&gt; Discovered with Uhuru, Active State, \( F_x \sim 3 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \)
(Formann et al. 1978)

1979-1982 --&gt; Optical and X-ray simultaneous observations:
(McGraw-Hill 1.3 m, Einstein, 63 ms)
- \(~5.2\) h modulated optical light curve
- Optical and X-ray phase mimima aligned
- \( \Delta B \sim 1.5 \) mag
- B-V (unknown \( A_v \)) + Roche Lobe Geometry

--&gt; M - K star, \( d \sim 2.2 - 4 \) kpc
- \( L_x/L_o \sim 10 \)
- X-Ray Spectrum:
  (2-10 keV)

\[
\frac{dF}{dE} = C e^{(-E_a/E)^{2/7} E^{-\alpha}}
\]
\( E_a < 1.2 \)
(cut-off)

No Phase Variation

McClintok et al., 1982,1981)
Active State: INTERPRETATION

- Eclipse --> \( i \sim 82^\circ \), parameters see picture
- Flux & Spectrum -->
  Compact Source surrounded by a Gas Cloud;
  Smoothness and Depth of the X-ray Eclipse:
  < 0.1 Flux at Max is due to the central source

Single Corona --> required \( \tau \) high (only 0.1 \( F_X \) obs.)
  + highly ionized (no spectral features)
  --> required \( L_X \sim 10^{38} \) erg s\(^{-1}\)
  --> unlikely \( d \sim 80 \) kpc

Double Corona --> optically thick inner corona block central source (90 %)
  + optically thin external corona
  (electron scattering, comptonization, power law spectrum)

**External Corona** --> Evaporation from the surface of the companion star,
gravitationally bound by the compact star (?)

**Internal Corona** --> Evaporation from the surface of the inner accretion disk
First 4U2129+47 Observation in Quiescence with Chandra

Nowak et al. (2002) --> ~37 Ks Chandra observation (~2 orbital period)

**INTERPRETATION**

- Collapse of the ADC of a factor ~5
- Thicker outer disk rim
- Modulation of the soft (<2 keV) light curve
- Coincident with the F star to within 0.1"

Fits to the X-Ray Spectra of 4U 2129+47 (90% Confidence Level Error Bars)

<table>
<thead>
<tr>
<th>Fit</th>
<th>$N_H$ ($10^{24}$ cm$^{-2}$)</th>
<th>$kT$ (keV)</th>
<th>$R_0$ or $D_0$ (km or kpc)</th>
<th>$A_T$ ($10^{-6}$)</th>
<th>$\Gamma$</th>
<th>0.5–2 keV b ($10^{-13}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>0.5–2 keV c ($10^{-13}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>2–8 keV ($10^{-13}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>A...</td>
<td>$3.1^{+0.8}_{-0.7}$</td>
<td>0.21$^{+0.02}_{-0.03}$</td>
<td>2.5$^{+0.5}_{-0.7}$</td>
<td>6.4$^{+0.22}_{-0.22}$</td>
<td>1.1$^{+1.1}_{-1.1}$</td>
<td>1.0</td>
<td>2.5</td>
<td>0.5</td>
<td>38.1 / 35</td>
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</table>
Inactive State: INTERPRETATION

Black Body ~0.2 keV, R~2.5 km

Residual Accretion (low luminosity) onto the NS

Power-law Component $E^{-\Gamma}$, $\Gamma \sim 1.1$

Shock between the pulsar electromagnetic radiation and matter from the companion (~$10^{10}$ cm) --> Power law during the eclipse $\Gamma \sim 1-2$

Shock at the interface between the neutron star magnetosphere and the accretion disk (~$10^7$ cm) --> No power law in the eclipse
Some Informations

4U2129+47
(eclipsing binary)

Position in Galactic Coordinate
but..
Uncertainties on the exact distance!!
A look into the past...

SUMMARY

ACTIVE STATE --> 1963-1983

INACTIVE STATE --> 1938-1943; 1983-??

(Wenzel et al, 1983)
Evolutionary Scenario LMXBs

Mechanisms driving mass transfer in LMXBs
(a) Loss of orbital angular momentum
   - Gravitational radiation
   - Magnetic braking
(b) Nuclear evolution of the companion star

(i) $P_{\text{orb, i}} > \sim 1-2 \text{ d}$ --&gt; the mass transfer is driven by the internal evolution of the low-mass (sub-)giant companion stars.

(ii) $P_{\text{orb}} < \sim 10 \text{ hr}$ --&gt; interior evolution of the companion plays a negligible role and the evolution of system is driven by angular momentum losses by magnetic braking and gravitational radiation.

(iii) In the intermediate period range between $\sim 10 \text{ hr}$ and $\sim 1-2 \text{ d}$, both angular momentum losses by magnetic braking and the radius expansion due to the interior evolution of the subgiant play a role.
Evolutionary Scenario LMXBs

ZAMS
- 15.0
- 1.6
- $P_{\text{orb}}$: 1500 days
- age: 0.0 Myr

Roche-lobe overflow
- 13.0
- 1.6
- $P_{\text{orb}}$: 1930 days
- age: 13.9 Myr

common envelope + spiral-in
- 4.86

helium star
- 4.86
- 1.6
- $P_{\text{orb}}$: 0.75 days
- age: 13.9 Myr

supernova
- 3.99
- 1.6
- $P_{\text{orb}}$: 1.00 days
- age: 15.0 Myr

neutron star
- 1.3
- 1.6
- $P_{\text{orb}}$: 2.08 days
- age: 15.0 Myr

LMXB
- 1.3
- 1.59
- $P_{\text{orb}}$: 1.41 days
- age: 2.24 Gyr
Comparison of focal plane organisation of EPIC MOS and pn cameras

**EPIC MOS**

- 7 CCDs each 10.9 x 10.9 arcminutes
- PSF FWHM ~6"/15" (1.5 keV)
- F.O.V. ~ 30'
- $A_{\text{eff}} \sim 400 \text{ cm}^2$ (1.5 keV)
- energy range 0.1-15 keV

**EPIC pn**

- 12 CCDs each 13.6 x 4.4 arcmin
- PSF FWHM ~6"/15" (1.5 keV)
- F.O.V. ~ 30'
- $A_{\text{eff}} \sim 1400 \text{ cm}^2$ (1.5 keV)
- energy range 0.1-15 keV

7 CCD
- PSF FWHM ~6"/15" (1.5 keV)
- F.O.V. ~ 30'
- $A_{\text{eff}} \sim 400 \text{ cm}^2$ (1.5 keV)
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12 CCD
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- F.O.V. ~ 30'
- $A_{\text{eff}} \sim 1400 \text{ cm}^2$ (1.5 keV)
- energy range 0.1-15 keV
Active State: INTERPRETATION

- Eclipse --&gt; $i \approx 82^\circ$, parameters see fig.
- Partial X-ray Eclipse --&gt; Compact Source surrounded by a Gas Cloud
- Modulation --&gt; orbital period $\sim 5.2$ h
- B-V, U-B + Geometry --&gt; M - K star
  
  $d \sim 1 - 2$ kpc ($L_X \sim 5 \times 10^{34}$ erg s$^{-1}$)

- Heated surface of the companion star ($L_{\text{opt}}$)

Accretion Disk Corona --&gt; Evaporation from the surface of the companion star, (gravitationally bound by the compact star) and from the inner accretion disk
The O-C residuals technique

\[ T_{\text{ref}} = 2444403.743 \pm 0.002 \text{ JD} \]
\[ P_{\text{ref}} = 18857.48 \pm 0.07 \text{ s} \]

\[ n \sim \frac{T_n - T_{\text{ref}}}{P_{\text{ref}}} \]
\[ T_{n-pred} = T_{\text{ref}} + n P_{\text{ref}} \]
\[ \Delta T = T_n - T_{n-pred} \]

FIT with:
\[ \Delta T = \alpha + \beta n + \gamma n^2 \]

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<tr>
<td>( P_{\text{orb}} \dot{P}_{\text{orb}} ) (yr)</td>
<td>(4.5 \pm 0.4) \times 10^{-6}</td>
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Triple System Consequences...

An interesting possibility.....

No orbital evolution required

Spin Up expected, no spin down!!!
(magnetic braking, gravitational wave)

Solve the problem of the “WRONG” orbital period derivative...

| T_{ref} (JD) | 2444403.743±0.001 |
| P_{orb} (s)  | 18857.585±0.007   |
| P_{orb} | (1.34±0.12)×10^{-10} |
| P_{orb} | (4.5±0.4)×10^{-6}    |
| χ^2/d.o.f. | 31/3                |