Soft X-ray Transients
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artwork courtesy T. Piro
Discovery, Cen X-4

THE RECENT APPEARANCE OF A NEW X-RAY SOURCE IN THE SOUTHERN SKY

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COUNT RATE, CPS

DATE JULY 1969

VELA 5A
VELA 5B
transients

Aql X-1
transients

Aql X-1
H-atmosphere; Zavlin et al. ‘96

heavier species rapidly sink from photosphere; Bildsten et al. ‘92
gives radii consistent with NS star surface
Quiescent emission consistent with emission from NS surface

Rutledge et al. ‘00
Fig. 2. Schematic representation of \((A, Z)\). The curves of constant \(\varepsilon_\beta = Q_p - Q_n\) have been indicated by dashed lines. The thick black line indicates the boundary of existence of a nucleus for which \(Q_n = 0\). The step line \(a_1a_2a_3 \ldots a_k\) correspond to variations of \((A, Z)\) with increasing density of the cold material. At the point \(a_k\), \(\varepsilon_\beta\) attains the maximum \(\varepsilon_{\beta \text{ max}}\).
illustration with a simple liquid-drop model (Mackie & Baym ’77, following Haensel & Zdunik ‘90)

see poster by A. Deibel

crust reactions | deep heating

Bisnovatyi-Kogan and Chechetkin ’74; Sato ’79; Haensel & Zdunk ’90; Gupta et al. ’07; Steiner ’12; Schatz et al. ’13; Deibel et al. (in prep)
neutronization

\[ E \approx -a_V (N + Z) + a_A \frac{(N - Z)^2}{N + Z} \]

In β-equilibrium, \( \mu_e = \mu_n - \mu_p \), with

\[ \mu_n = \left( \frac{\partial E}{\partial N} \right)_Z, \quad \mu_p = \left( \frac{\partial E}{\partial Z} \right)_N \]

\[ \frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A} \]
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In $\beta$-equilibrium, $\mu_e = \mu_n - \mu_p$, with

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At neutron drip, 

\[ \mu_n = \left( \frac{\partial E}{\partial N} \right)_Z \rightarrow 0 \]

\[ \mu_e \approx 2a_V \approx 30 \text{ MeV} \]
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At neutron drip,

\[ \mu_n = \left( \frac{\partial E}{\partial N} \right)_Z \to 0 \]

\[ \mu_e \approx 2a_V \approx 30 \text{ MeV} \]
\[ Q = \langle Z^2 \rangle - \langle Z \rangle^2 \]

1.8 MeV/u released

not much heat from electron captures

neutron drip

plot courtesy A. Steiner
L_q = Q(\dot{M})

\log L_{\text{NS}} \text{ (erg s}^{-1})

\sim T_{\text{core}}

T_{\text{core}} \approx 2 \times 10^8 K \left( \frac{\langle \dot{M} \rangle}{10^{-10} M_\odot \text{ yr}^{-1}} \right)^{1/8}

T_{\text{core}} \approx 2 \times 10^7 K \left( \frac{\langle \dot{M} \rangle}{10^{-10} M_\odot \text{ yr}^{-1}} \right)^{1/6}

\sim \text{crustal heating}

\log \dot{M} \text{ (} M_\odot \text{ yr}^{-1})

\sim \text{crustal heating}
For KS 1731 that all outbursts from NGC 6440 since 1971 have been detected. (Rutledge et al. 2002; Campana & Stella 2003). We plot an arbitrary gram and thus the conversion from NS mass and radius (affecting the energy released per accreted mass transfer rate (Table 2). We use PIMMS and a averaged mass transfer rate (Table 2). We use PIMMS and a

\[ \frac{L}{10^{32} \text{erg s}^{-1}} = \frac{\langle \dot{M} \rangle}{10^{-10} \text{M}_\odot \text{yr}^{-1}} \]

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determination of NS radius
Guillot et al. 2013
H vs He atmosphere
NGC 6397, Heinke et al. ‘14
quasi-persistent transients

Cackett et al. ‘06
quasi-persistent transients

Rutledge et al., Shternin et al., Brown & Cumming; Page & Reddy
quasi-persistent transients

Rutledge et al., Shternin et al., Brown & Cumming; Page & Reddy
quasi-peristent transients

Rutledge et al., Shternin et al., Brown & Cumming; Page & Reddy

data from Cackett et al. 2008
fits from Brown & Cumming 2009
basic physics of the lightcurve

For a cooling crust,

\[ \rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left( K \frac{\partial T}{\partial r} \right), \]

and a cooling front propagates into crust on a timescale

\[ \tau \approx \frac{1}{4} \left[ \int \left( \frac{\rho C_P}{K} \right)^{1/2} \, dr \right]^2. \]
basic physics of the lightcurve

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How impure is the crust? $Q < 10$

Shternin et al. 2007; Brown & Cumming 2009; see talk by D. Page

\begin{itemize}
  \item Observations
  \begin{align*}
    Q = 0, & \quad T_{b,8} = 3.8 \\
    Q = 1, & \quad T_{b,8} = 3.8 \\
    Q = 4, & \quad T_{b,8} = 3.8 \\
    Q = 10, & \quad T_{b,8} = 3.8 \\
  \end{align*}
\end{itemize}
How impure is the crust? $Q < 10$

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\begin{align*}
\langle Z - \langle Z \rangle \rangle^2 &= 0 - 10
\end{align*}
Superburst in 4U 1608–522
Keek et al. ’07

Temperature needed for thermally unstable ignition of $^{12}$C+$^{12}$C if $\sigma$ is CF.
Strong neutrino cooling by cycles of electron capture and $\beta^-$ decay in neutron star crusts

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• How it works

• Why it wasn’t noticed before

• What it means for X-ray bursts and superbursts
illustration with a simple liquid-drop model (Mackie & Baym ’77, following Haensel & Zdunik ‘90)

see poster by A. Deibel

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Review | electron captures

(Bisnovatyi-Kogan & Chechetkin; Sato; Haensel & Zdunik; Gupta et al.)

\[ E_{\text{thr,gs-gs}} = E^Z_{\text{thr,gs-gs}} + E_{\text{exc}} \]
Composition: \((Z,A)\)

Urca shell: both \((Z,A)\) and \((Z-1,A)\)

Composition: \((Z-1,A)\)
Urca pairs | which nuclei?
Necessary conditions
1. low-lying transitions: $E_x < kT$
2. no strong EC branch for daughter nucleus
Compare neutrino luminosities

\[ L_{\nu} = \frac{\alpha_{\nu}^2 T_{\nu}^2}{\pi} \]

\[ \alpha_{\nu} = \frac{\pi}{\langle E_{\nu} \rangle} \]

Crust heating

- Tsuruta & Cameron 1970
- Superburst ashes
- Rp-process ashes
- Bremsstrahlung
- Plasmon

Temperature (K) vs. Neutrino luminosity (erg s\(^{-1}\))
Urca shell | cold layer

\[ \dot{M} = 3.0 \times 10^{17} \text{ g s}^{-1} \]
cf. Gupta et al. ’07

![Graph showing temperature versus pressure for different cooling scenarios.](image-url)

- No Urca shell cooling
- L/\dot{M} = 0.064 \text{ MeV/u}
- 0.020 \text{ MeV/u}
- -0.003 \text{ MeV/u}
Urca shell | cold layer

\[ \dot{M} = 3.0 \times 10^{17} \text{ g s}^{-1} \]

cf. Gupta et al. '07

\[ \dot{\Gamma} \]

\[ \text{Density (g cm}^{-3}\text{)} \]

- no Urca shells
- HFB21
- FRDM

\text{crust}

\text{ocean}
superburst | ignition

heating occurs here

No Urca shell cooling

FRDM

HFB-21

Temperature (GK)

\( P/g \) (g cm\(^{-2}\))
Facility for Rare Isotope Beams

Michigan State University
Urca pairs | which nuclei?
conclusions

- Soft X-ray transients provide information on physics of interior
  - radii from surface thermal emission
  - thermal conductivity, specific heat of crust from cooling
  - electron captures/beta decays in outer crust set a limit on the crust temperature: need additional heating in outer crust to explain superbursts?