EXTRA CREDIT

Find as many mistakes as you can and correct them!

Cite your source for the lyrics and astronomical data.
Show any math/conversions explicitly.

Due: Last day of classes, May 1
Room Change

Monday April 20, 2009
BioChem room 111
X-ray binaries
– nuclear physics at the extremes

Outline

1. Observations
2. X-ray Burst Model
3. Nuclear Physics – the rp process
4. Open Questions
Wilhelm Konrad Roentgen, First Nobel Price 1901 for discovery of X-rays 1895

First X-ray image from 1890
(Goodspeed & Jennings, Philadelphia)

Ms Roentgen’s hand, 1895
Cosmic X-rays: discovered end of 1960’s:

0.5-5 keV (T=E/k=6-60 \times 10^6 K)

Again Nobel Price in Physics 2002 for Riccardo Giacconi
X-rays in the sky

Some X-ray Landmarks

- NGC 4151 massive black hole
- Cyg X-1 stellar black hole
- Cas A supernova remnant
- Sun

Crab nebula and pulsar
- Cen X-3
- Large Magellanic Cloud

- GX 17+2
- GX 1+4
- GX 349+2 neutron star
- GX 5-1

D.A. Smith, M. Muno, A.M. Levine, R. Remillard, H. Bradt 2002
(RXTE All Sky Monitor)
First **X-ray pulsar**: Cen X-3 (Giacconi et al. 1971) with UHURU

**First X-ray burst**: 3U 1820-30 (Grindlay et al. 1976) with ANS

**Today**: ~50 burst sources out of 160 LMXB’s

**Total ~230 X-ray binaries known**
Burst characteristics

Typical X-ray bursts:

- $10^{36}$-$10^{38}$ erg/s
- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon!

(stars $10^{33}$-$10^{35}$ erg/s)
Neutron stars:
1.4 $M_\odot$, 10 km radius
(average density: $\sim 10^{14}$ g/cm$^3$)

Typical systems:
- accretion rate $10^{-8}/10^{-10} \ M_\odot$/yr (0.5-50 kg/s/cm$^2$)
- orbital periods 0.01-100 days
- orbital separations 0.001-1 AU’s
- surface density $\sim 10^6$ g/cm$^3$
Observation of thermonuclear energy

Unstable, explosive burning in bursts (release over short time)

- Burst energy
- Thermonuclear

- Persistent flux
- Gravitational energy
Energy sources

Energy generation: thermonuclear energy

\[ 4\text{H} \rightarrow ^4\text{He} \quad 6.7 \text{ MeV/u} \quad \text{("CNO cycles")} \]

\[ 3^4\text{He} \rightarrow ^{12}\text{C} \quad 0.6 \text{ MeV/u} \quad \text{("triple alpha")} \]

\[ 5\; ^4\text{He} + 84\; \text{H} \rightarrow ^{104}\text{Pd} \quad 6.9 \text{ MeV/u} \quad \text{("rp process")} \]

Energy generation: gravitational energy

\[ E = \frac{G \; M \; m_u}{R} = 200 \text{ MeV/u} \]

Ratio gravitation/thermonuclear \( \sim 30 - 40 \) (called \( \alpha \))
Initial Conditions

- Accreting material loses energy via X-ray emission
  - Gravitational energy
- Surface temperature related to accretion rate
  - Kinetic energy
Burst ignition at “low” accretion rates

Burst trigger rate is “triple alpha reaction”  $^3\,^4\text{He} \rightarrow ^{12}\text{C}$

Ignition: $\left| \frac{d\varepsilon_{\text{nuc}}}{dT} \right| > \left| \frac{d\varepsilon_{\text{cool}}}{dT} \right|$

$\varepsilon_{\text{nuc}}$ Nuclear energy generation rate

$\varepsilon_{\text{cool}} \sim T^4$ Cooling rate

Ignition < 0.4 GK: unstable runaway

- heat added increases T
- higher T increases $\varepsilon_{\text{nuc}}$
- larger $\varepsilon_{\text{nuc}}$ increase T more
Stable burning at “high” accretion rates

Stable Burning: \[ \left| \frac{d\varepsilon_{\text{nuc}}}{dT} \right| < \left| \frac{d\varepsilon_{\text{cool}}}{dT} \right| \]

\( \varepsilon_{\text{nuc}} \) Nuclear energy generation rate
\( \varepsilon_{\text{cool}} \sim T^4 \) Cooling rate

Stable Burning > 0.5 GK:
- heat added efficiently cooled
- \( T \) doesn’t change dramatically

\[ \text{NO X-Ray Bursting!!} \]
Visualizing reaction networks

Proton number

\[
\begin{array}{c}
\text{27Si} \\
\text{13} \\
\end{array}
\]

\[
\begin{array}{c}
\text{14} \\
\text{Proton number} \\
\end{array}
\]

\[
\begin{array}{c}
\text{13} \\
\text{neutron number} \\
\end{array}
\]

- \((p, \gamma)\)
- \((\alpha, \gamma)\)
- \((\alpha, p)\)
- \((, \beta^+)\)
**“Cold” CN(O)-Cycle**  \( T_9 < 0.08 \)

Energy production rate:
\[ \varepsilon \propto <\sigma v>_{14N(p,\gamma)} \]

**Hot CN(O)-Cycle**  \( T_9 \sim 0.08-0.1 \)

“beta limited CNO cycle”
\[ \varepsilon \propto 1/(\lambda_{14O(\beta^+)}^{-1} + \lambda_{15O(\beta^+)}^{-1}) = \text{const} \]

Note: condition for hot CNO cycle depend also on density and \( Y_p \):

- on \(^{13}\text{N} \):
  \[ \lambda_{p,\gamma} > \lambda_\beta \]
  \[ \Leftrightarrow Y_p \rho N_A < \sigma v > > \lambda_\beta \]

- \(^{14}\text{O} \):
  \[ T_{1/2} = 71 \text{s} \]
- \(^{15}\text{O} \):
  \[ T_{1/2} = 122 \text{s} \]
**Very Hot CN(O)-Cycle**  \( T_9 \sim 0.3 \)

still “beta limited”

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**Breakout**

processing beyond CNO cycle after breakout via:

\[ T_9 > 0.36 \quad ^{15}O(\alpha,\gamma)^{19}Ne \]

\[ T_9 > 0.62 \quad ^{18}Ne(\alpha,p)^{21}Na \]

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**How do we calc?**

\[ ^{18}Ne \text{ T}_{1/2} = 1.7s \]

\[ ^{15}O \text{ T}_{1/2} = 122s \]
Current $^{15}$O(a,γ) Rate with X10 variation

New lower limit for density from B. Davids et al. (PRC67 (2003) 012801)
No Breakout

$^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ Breakout

$^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ Breakout

Gorres, Weischer and Thielemann
PRC 51 (1995) 392
Doubly Magic Nuclei influence nucleosynthesis

$^{40}$Ca – end of $\alpha$p-process

$^{56}$Ni – peak luminosity

$^{100}$Sn – end of rp-process

(Schatz et al. PRL 86(2001)3471)

Collaborators:

L. Bildsten (UCSB)
A. Cumming (UCSC)
M. Ouellette (MSU)
T. Rauscher (Basel)
F.-K. Thielemann (Basel)
M. Wiescher (Notre Dame)
- $\alpha p$ & rp competition
  - Important branching points
- past $^{40}\text{Ca}$, $\alpha$-induced reactions inhibited
  - rp-process continues
- Most energy generated near $^{56}\text{Ni}$
  - Can develop cycles
  - Heavy $\alpha$-nuclei are waiting points
- $^{100}\text{Sn}$ region natural endpoint
Competition between $\alpha p$- & $rp$- processes

- $^{22}\text{Mg}$ is branching point
- $(p,g)$ and $(a,p)$ compete
- $rp$-process eats $p$'s
- $\alpha p$-process eats $\alpha$'s

Branch points also appear at $^{26}\text{Si}$, $^{30}\text{S}$ & $^{34}\text{Ar}$
$^{56}\text{Ni}$ is doubly magic

$^{59}\text{Cu}$ is branch point

Either rp-continues

or (p,α) back to $^{56}\text{Ni}$

This is the NiCu cycle

Cycle pattern repeats for $^{60}\text{Zn}$

This is the ZnGa cycle
Slow reactions $\rightarrow$ extend energy generation $\rightarrow$ abundance accumulation

(steady flow approximation $\lambda Y = \text{const}$ or $Y \sim 1/\lambda$)

Critical "waiting points" can be easily identified in abundance movie
The Sn-Sb-Te cycle

Known ground state
α emitter

(Schatz et al. PRL 86(2001)3471)

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Experiments in the rp-process

Henrique Bertulani
Data needs for rp process

Key nuclear physics parameters:
- Proton separation energies (masses)
- $\beta$-decay half-lives
- Proton capture rates

\[ N=Z \text{ line} \]

$\beta^+$ and $(p, \gamma)$ half-life of $^{68}\text{Se}$

Exp. limit

- Hilf et al. mass
- Jaenecke et al. mass
- FRDM (1992) mass
- Upper limit from exp.

Schatz et al.
Experimental data?

- Mass known < 10 keV
- Mass known > 10 keV
- Only half-life known
- seen

Most half-lives known
Masses still need work
(need < 10 keV accuracy)
mass models not the issue
(extrapolation, coulomb shift)
Reaction rates?
Influence of masses on X-ray burst models

- **Brown**
- **Audi unbound**
- **Audi bound**
Problem: Reaction rates

Are important when:

- they draw on equilibrium
- they are slow – low T (ignition, cooling, upper layers)
- several reactions compete

Theoretical reaction rate predictions:

Hauser-Feshbach: not applicable near drip line

Shell model: available up to A~63 but large uncertainties (often x1000 - x10000)

(Herndl et al. 1995, Fisker et al. 2001)

→ Need radioactive beams
Comparison to Observations

Average XRB Light Curve


Flux ($10^{-9}$ erg cm$^{-2}$ s$^{-1}$) vs Time (s)
Model Comparisons

Summary

- rp-process is important to understand
  - X-ray bursts
  - crusts of accreting neutron stars/ transients
  - neutron stars!

- need radioactive beam experiments
  - much within reach at existing facilities
  - with RIA and FAIR precision tests possible

- lots of open question – much work to do
  - modelling
  - nuclear physics (predict instabilities?)
  - observations