

Nuclear Waiting Points and Double Peaked X-Ray Bursts

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THE NUCLEAR REACTION WAITING POINTS: ^{22}Mg , ^{26}Si , ^{30}S , AND ^{34}Ar
AND BOLOMETRICALLY DOUBLE-PEAKED TYPE I X-RAY BURSTS

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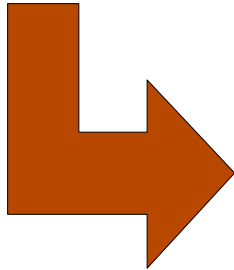
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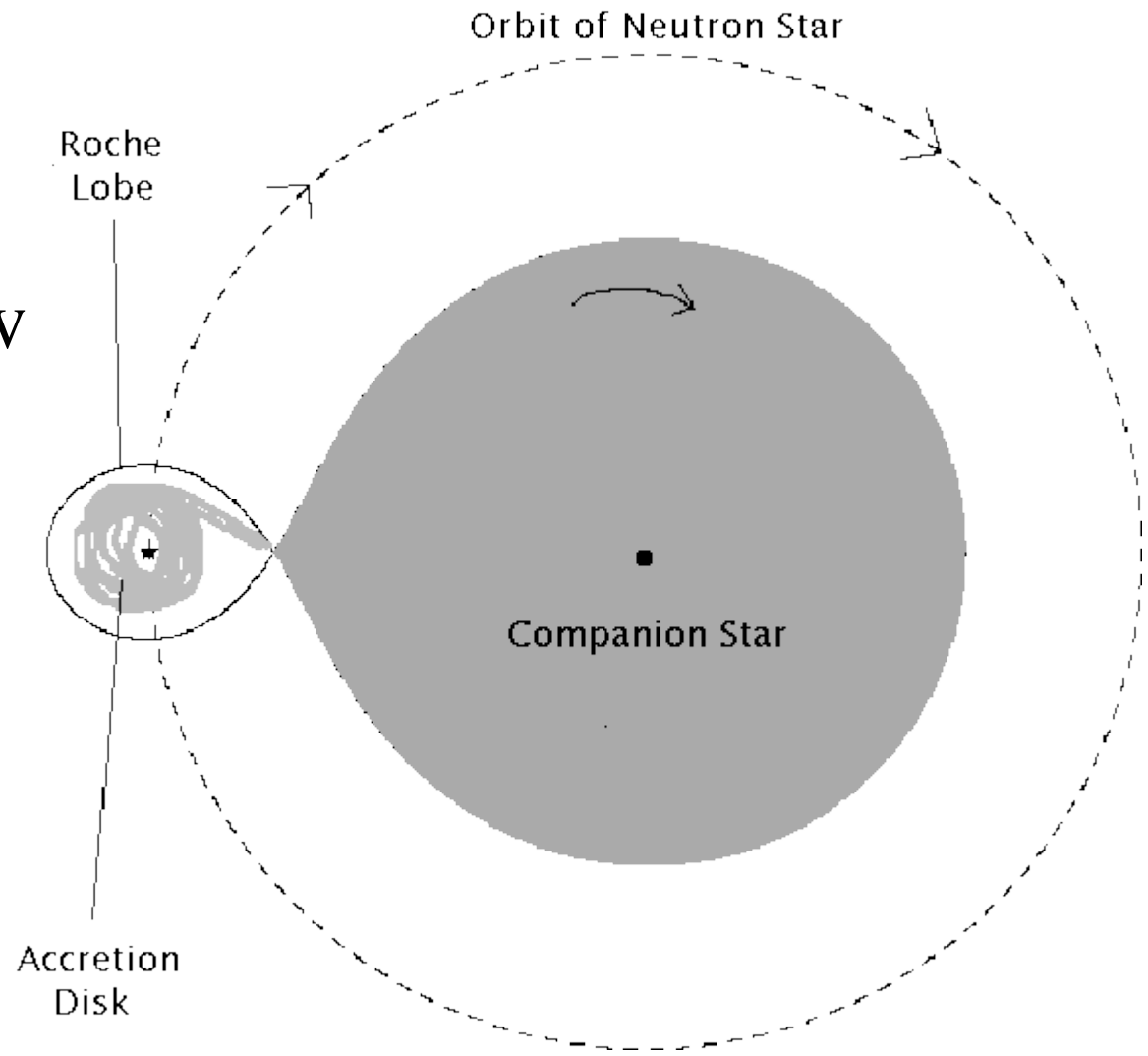
Presented 2007 April 04

A Brief Overview

- Accretion in Binary Star Systems
- Double Peaked X-Ray Bursts
- Nuclear Burning Pathways
- Impact of (α, p) reaction rate on models
- Propose $^{30}\text{S}(\alpha, p)^{33}\text{Cl}$ as primary waiting point
- Summary

Accretion on a Compact Object

- Roche Lobe Overflow
 - System of interest
- Stellar Wind
 - Requires massive partner



Results of Accretion

- High g , High v , High T
- Fresh Supply of H and He
- Degenerate Matter Leads to Explosive Burning
 - P only weakly depends on T
 - Surface layers electron degenerate, not neutron degenerate
- Contrast with stellar core burning
- Novae, Type Ia SNe, Pulsars, X-ray Bursts
 - Type I, II X-ray Bursters
 - Low-Mass versus Massive Binaries

4U 1636-53

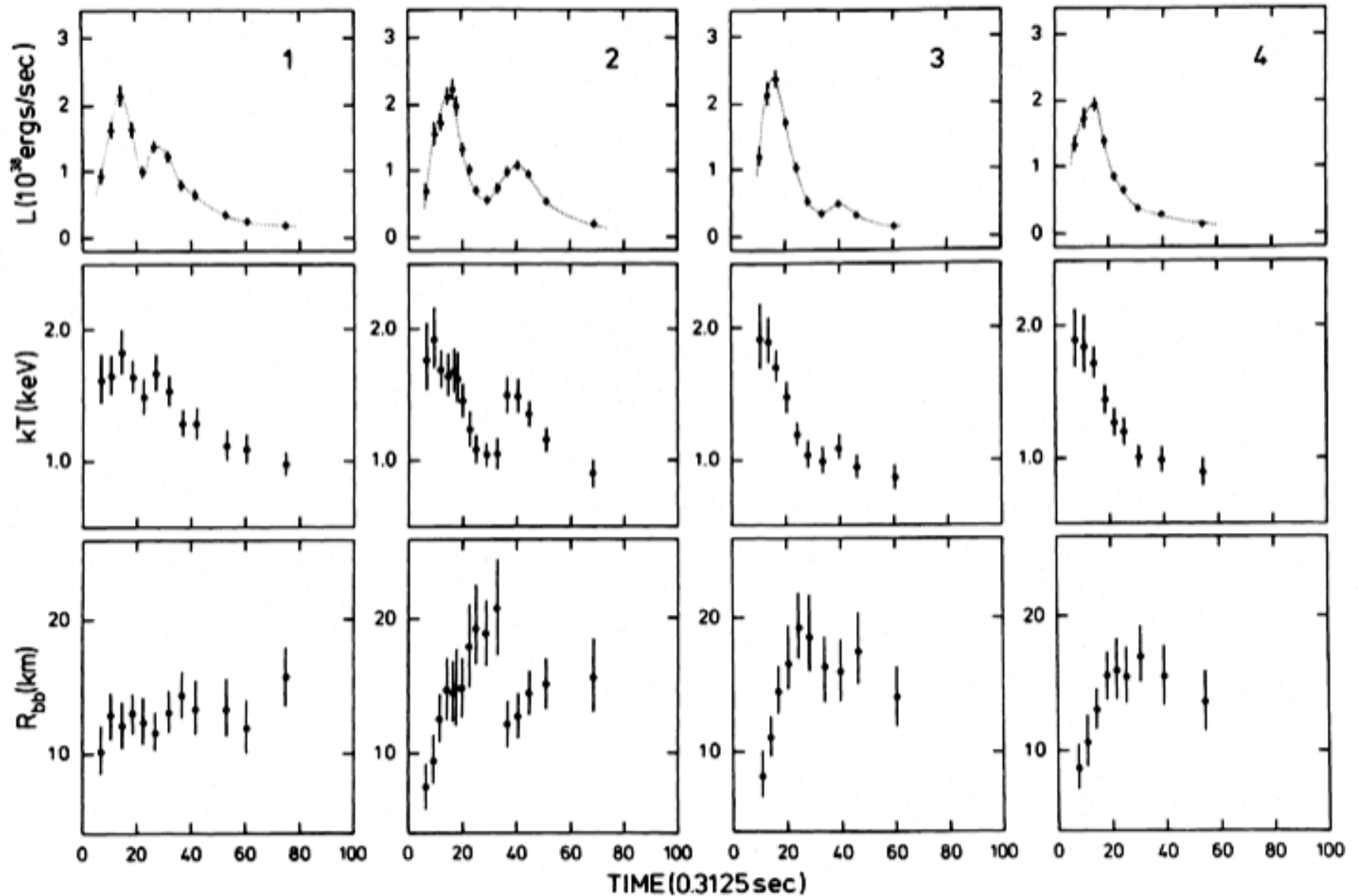


FIG. 2.—Variations of the bolometric luminosity (for an assumed distance of 10 kpc), the blackbody (color) temperature and the apparent blackbody radius during the eight X-ray bursts observed from 4U/MXB 1636-53.

4U 1636-53

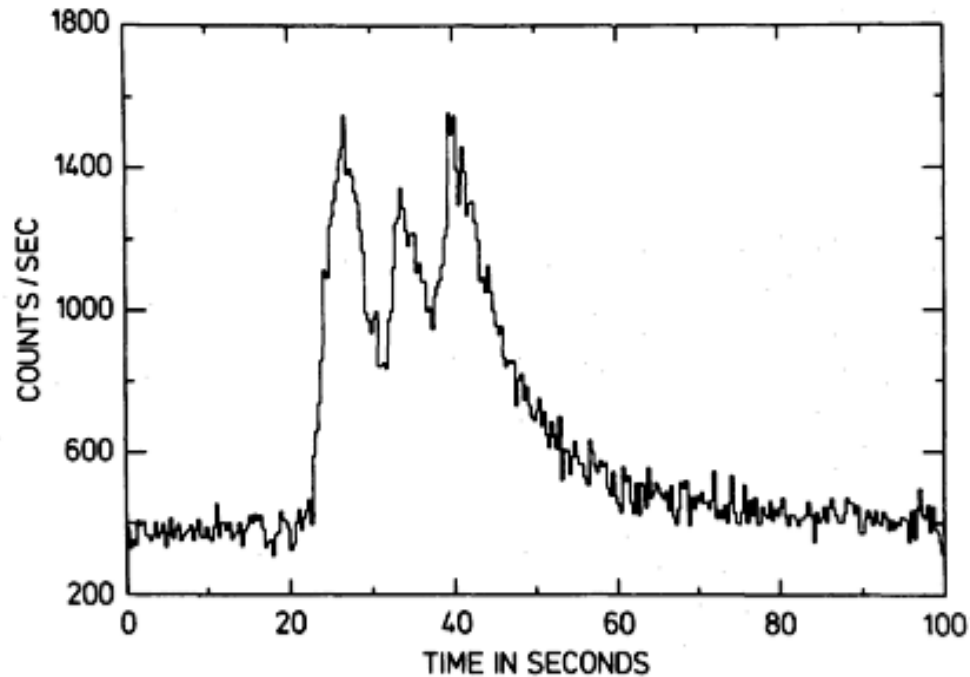


Figure 1. Raw counting-rate profile (1–20 keV) of the triple-peaked burst observed from 4U/MXB 1636–53 (no dead-time corrections have been made yet). Zero time is 1985 August 9, UT 15^h 01^m 50^s.

4U 1636-53

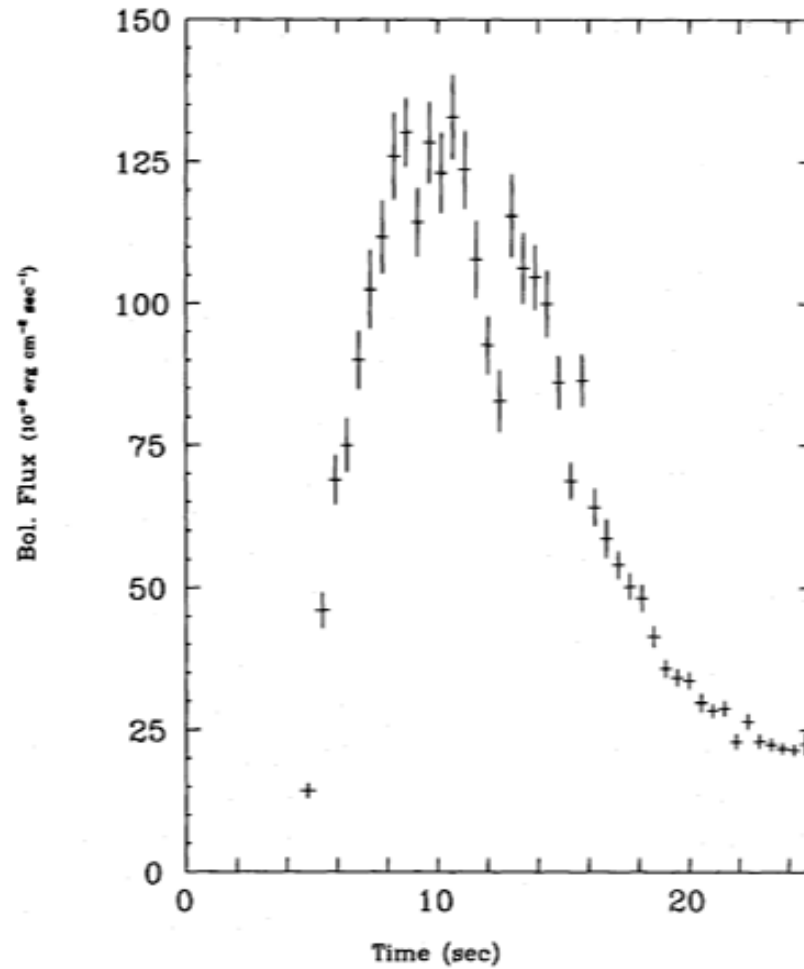


Fig. 5. Bolometric flux of the 1986 burst, notice the ~25% dip

GX 17+2

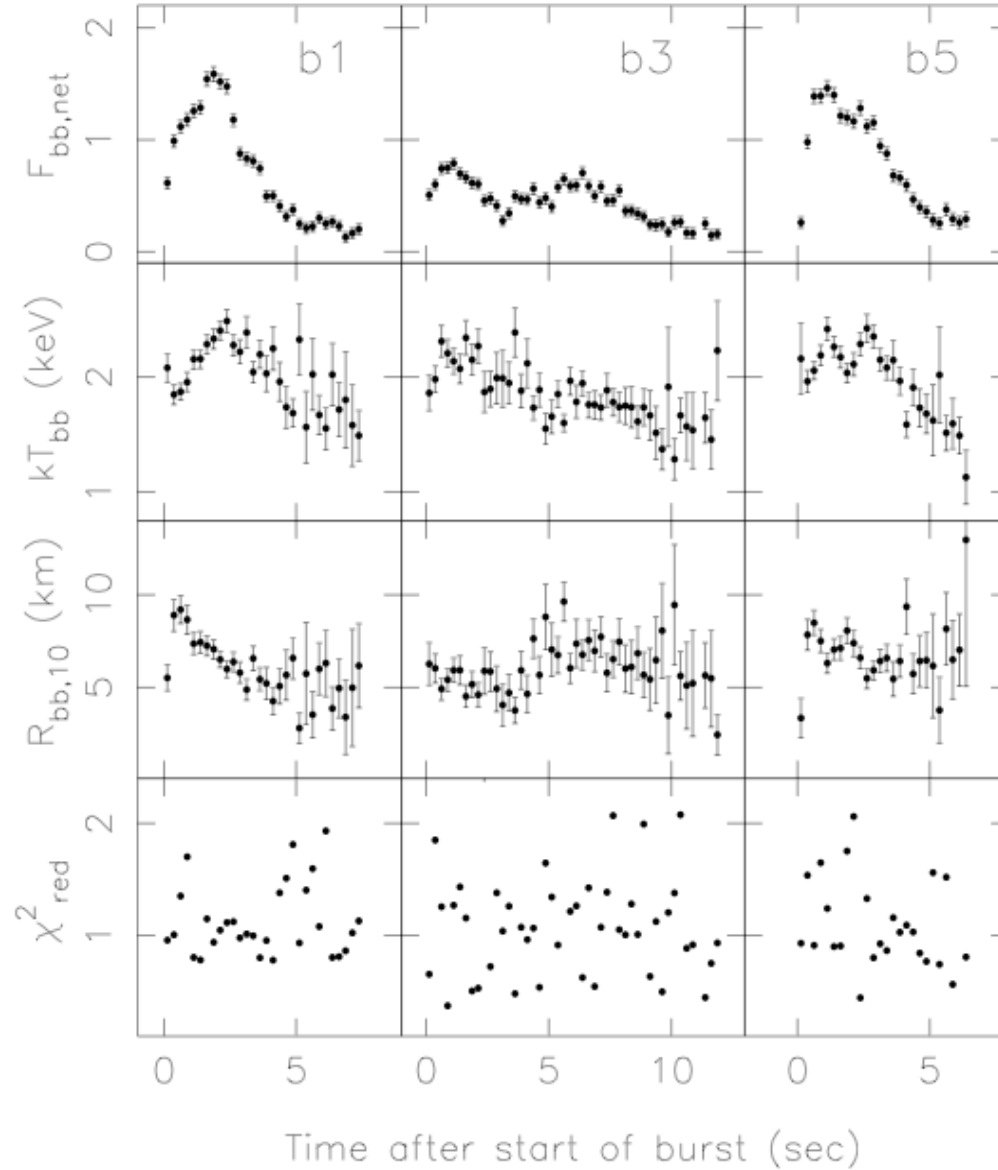


Fig. 11. Spectral fit results for the net burst emission of burst b1, b3 and b5; from top to bottom: bolometric black-body flux, $F_{\text{bb,net}}$, in $10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$, black-body temperature, kT_{bb} , apparent black-body radius, $R_{\text{bb},10}$, at 10kpc, and goodness of fit expressed in reduced χ^2 . The number of d.o.f. is 22 for burst b1 and 18 for bursts b3 and b5.

Proposed Explanations

- Radius Expansion
 - Satellite counters
- Heat Transport Impedence
 - Coarse-zone modelling
- Spatially Localized Burning Region
 - Frequency
- Accretion Disk Scattering
 - Recurrence time, fluence, peak flux
- Multiple Release of Nuclear Energy

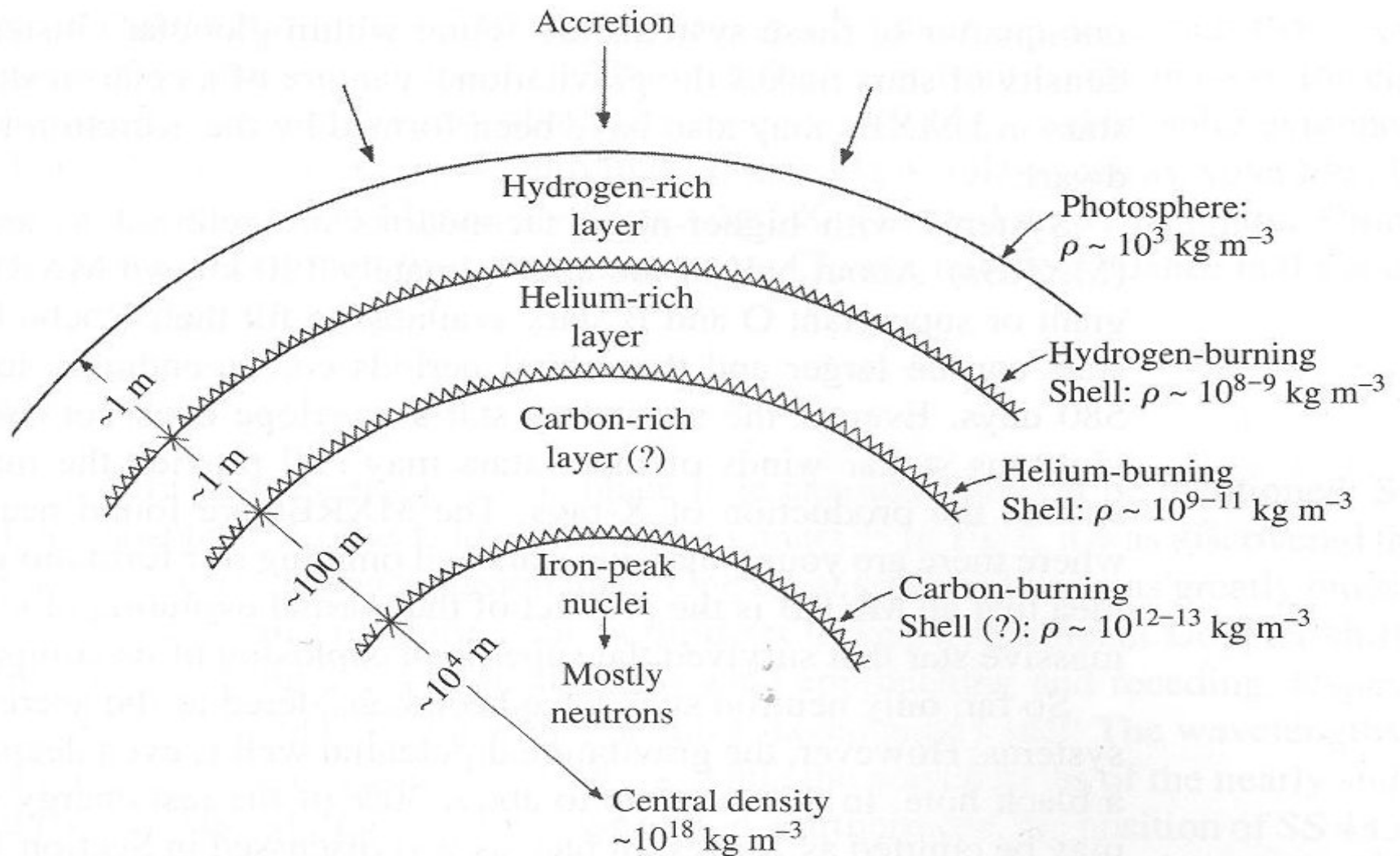
Paper Thesis

“In this Letter we propose that an interaction between the helium flash shell and a waiting point impedence in the *rp*-process of the shells above it explains burst shape structure spanning over the timescale of a few seconds.”

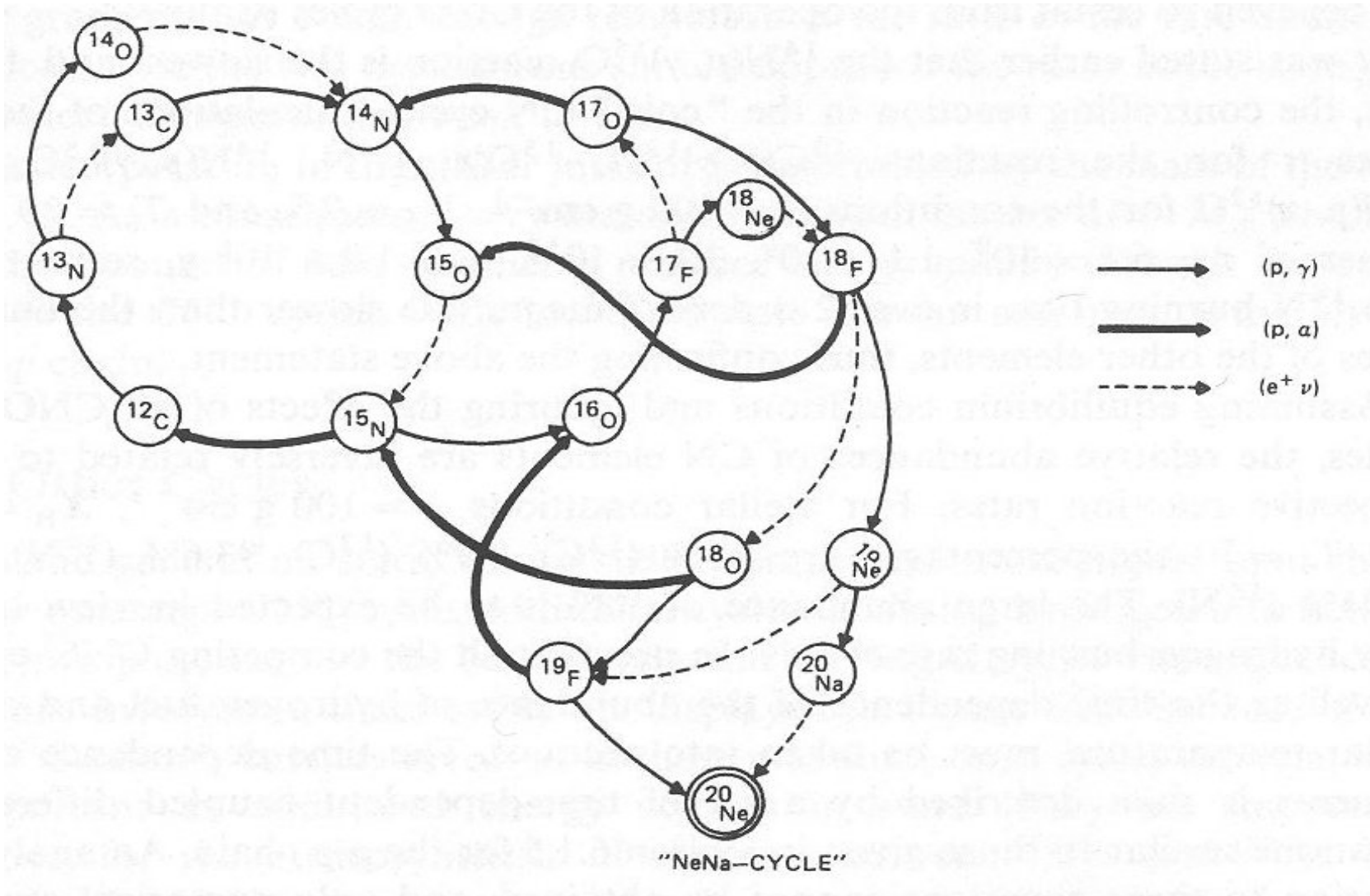
Assumed Initial Conditions

- Low mass binary systems
- Accretion material of solar composition
 - Anders & Grevesse 1989
- Atmosphere $T = 0.1 - 0.2$ GK
- β -limited hot CNO cycle
- Constant accretion rate of 7.65×10^{-6} solar masses/year
 - 4.5% of the Eddington accretion rate

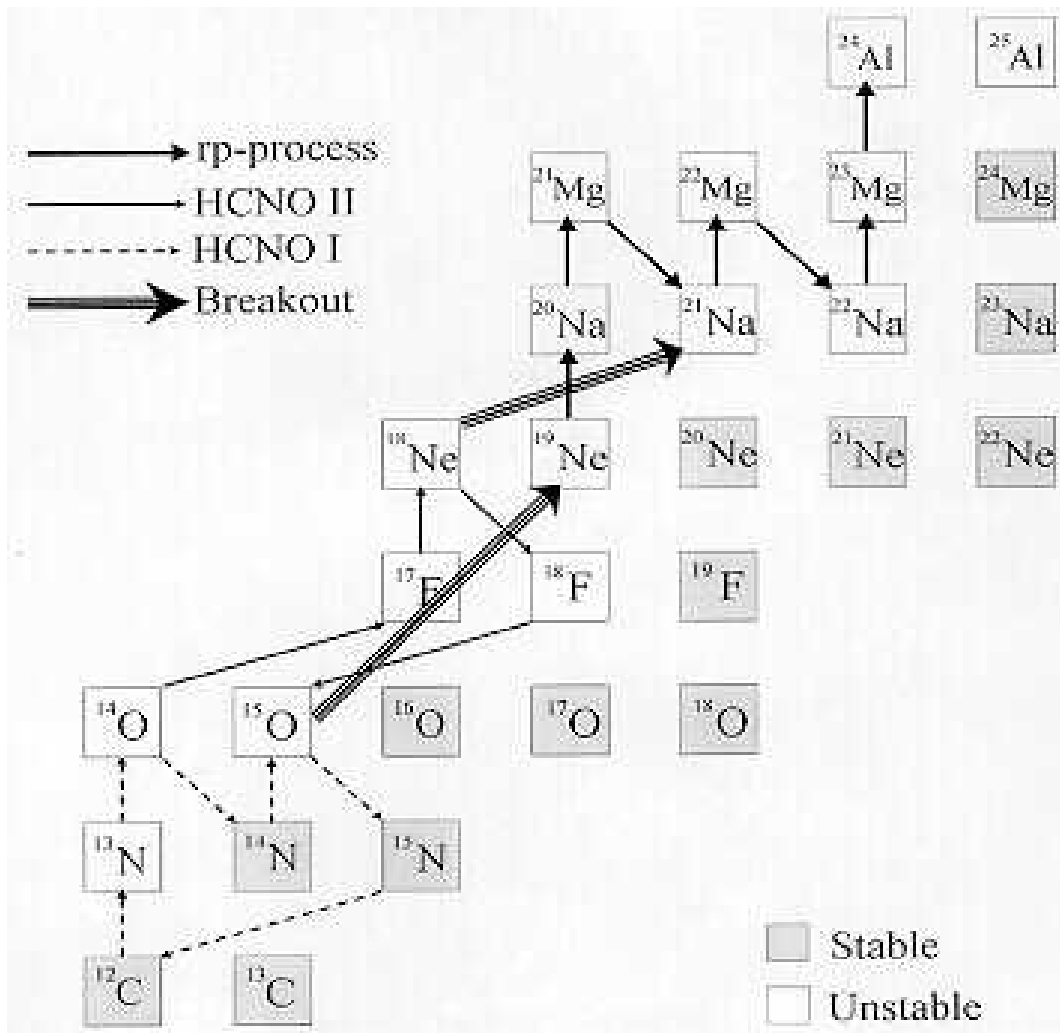
Neutron Star Cross Section



β -limited hot CNO Cycle



Hot CNO Breakout



- CNO are seed nuclei
- $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$
- $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$
- *rp*-process
- (α, p) -process

rp-process

- Rapid Proton capturing
- Moves CNO seed towards proton drip line
- Timescale set by β^+ -decays towards stability
- (p,γ) - (γ,p) equilibrium at even- Z nuclei
 - ^{22}Mg , ^{30}S , ^{34}Ar have low Q_p values (126, 296, 78 keV)
 - ^{26}Si has a higher Q_p value (859 keV)
- β^+ -decays at even- Z nuclei take more than 1 second!
- (α,p) reactions begin to compete with *rp*-process

Just to clear up any confusion...

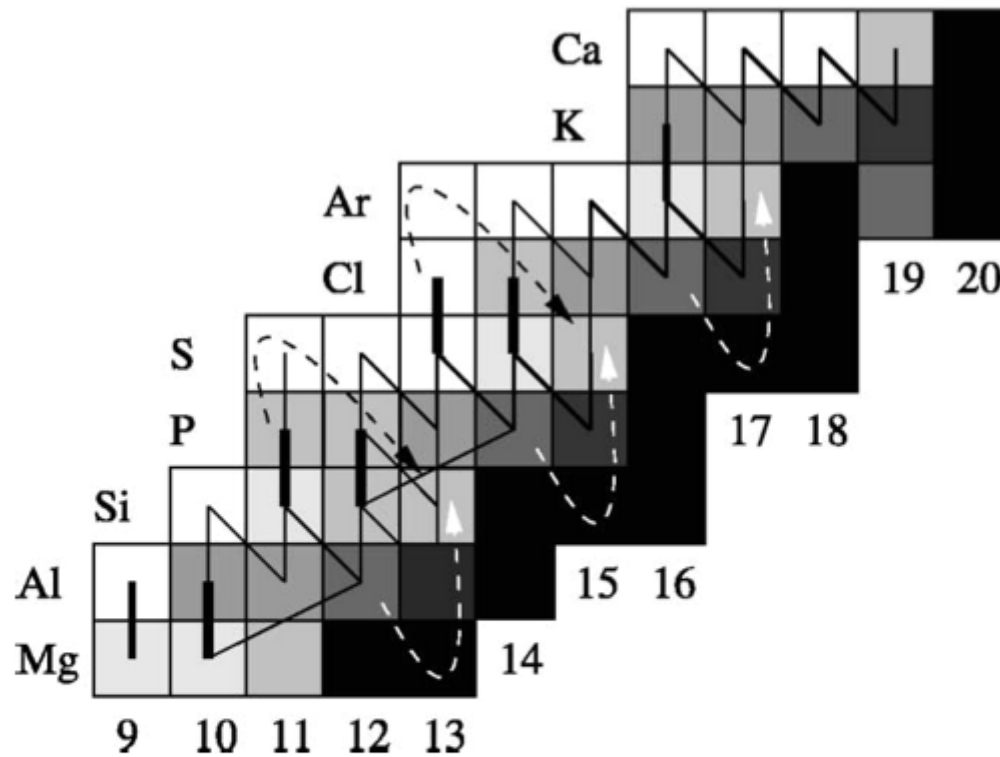
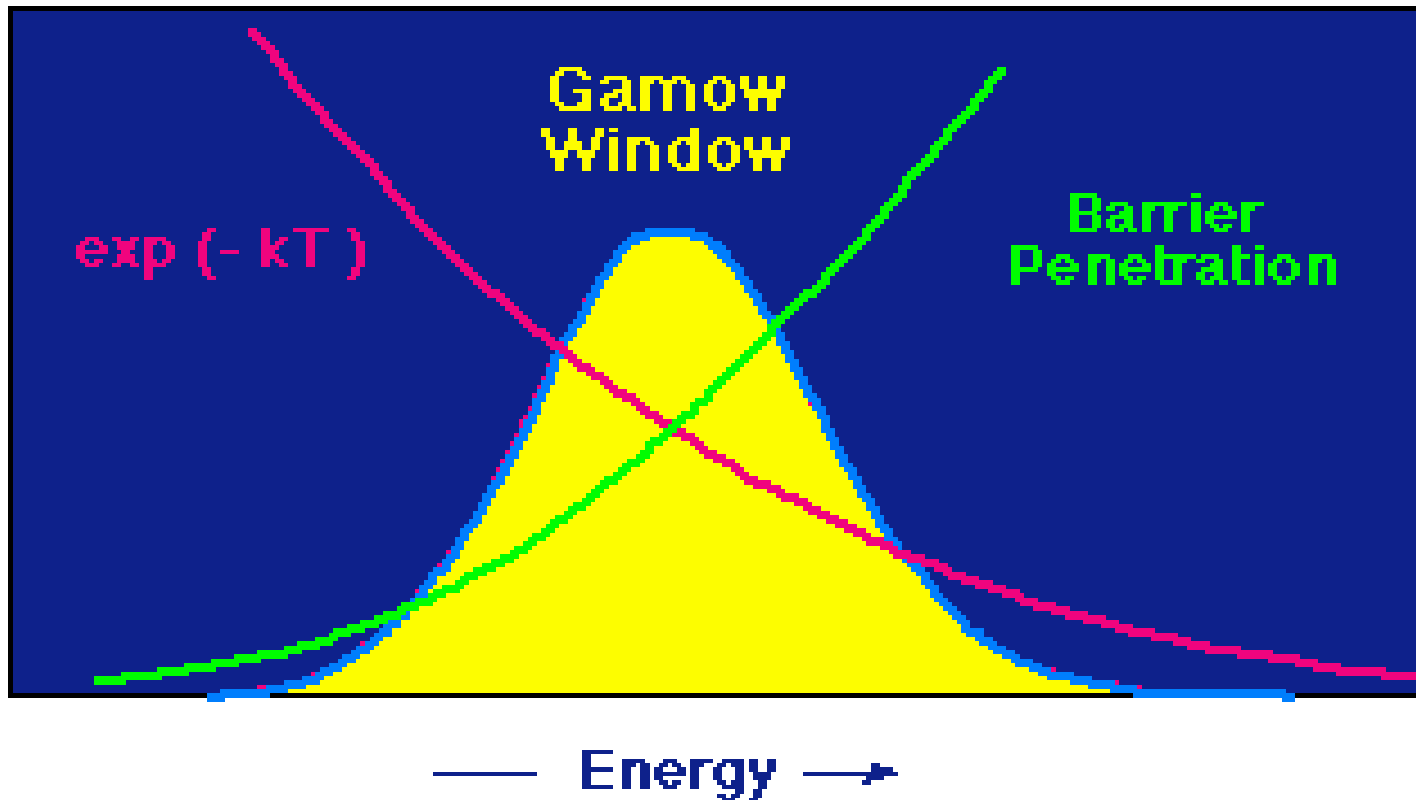


FIG. 1.—Targets with (p, γ) Q -values of ≤ 0.0 , $0.0-0.5$, $0.5-2.5$, $2.5-3.5$, $3.5-5.5$, and $5.5-8.0$ in increasing levels of gray. Stable nuclei are colored black. The reaction flow rates, $f_{ij} = \dot{Y}_{i \rightarrow j} - \dot{Y}_{j \rightarrow i}$, during the burst peak temperature are shown with solid lines. The thickness indicates the strength of the reaction flow with the exception of isotopes in (p, γ) - (γ, p) equilibrium, which are shown in thick lines although the net flow is close to zero. The reaction paths that circumvent the waiting points are indicated with dashed arrows.

(α, p) reactions

- Higher Coulomb barrier than rp -process
 - Very temperature dependent
- Under initial temperature conditions, we have:
 - $^{14}\text{O}(\alpha, p)^{17}\text{F}$
 - $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$
 - $^{22}\text{Mg}(\alpha, p)^{25}\text{Al}$
 - $^{26}\text{Si}(\alpha, p)^{29}\text{P}$
- We will not have:
 - $^{30}\text{S}(\alpha, p)^{33}\text{Cl}$
 - $^{34}\text{Ar}(\alpha, p)^{37}\text{K}$

Gamow Window



Maxwellian velocity distribution overlap with Coulomb barrier
~100 keV for α -capture in this environment

$$\lambda_{\beta+} = N_A \varrho Y_{\alpha} \Delta(T) \langle \sigma v \rangle_{(\alpha,p)}$$

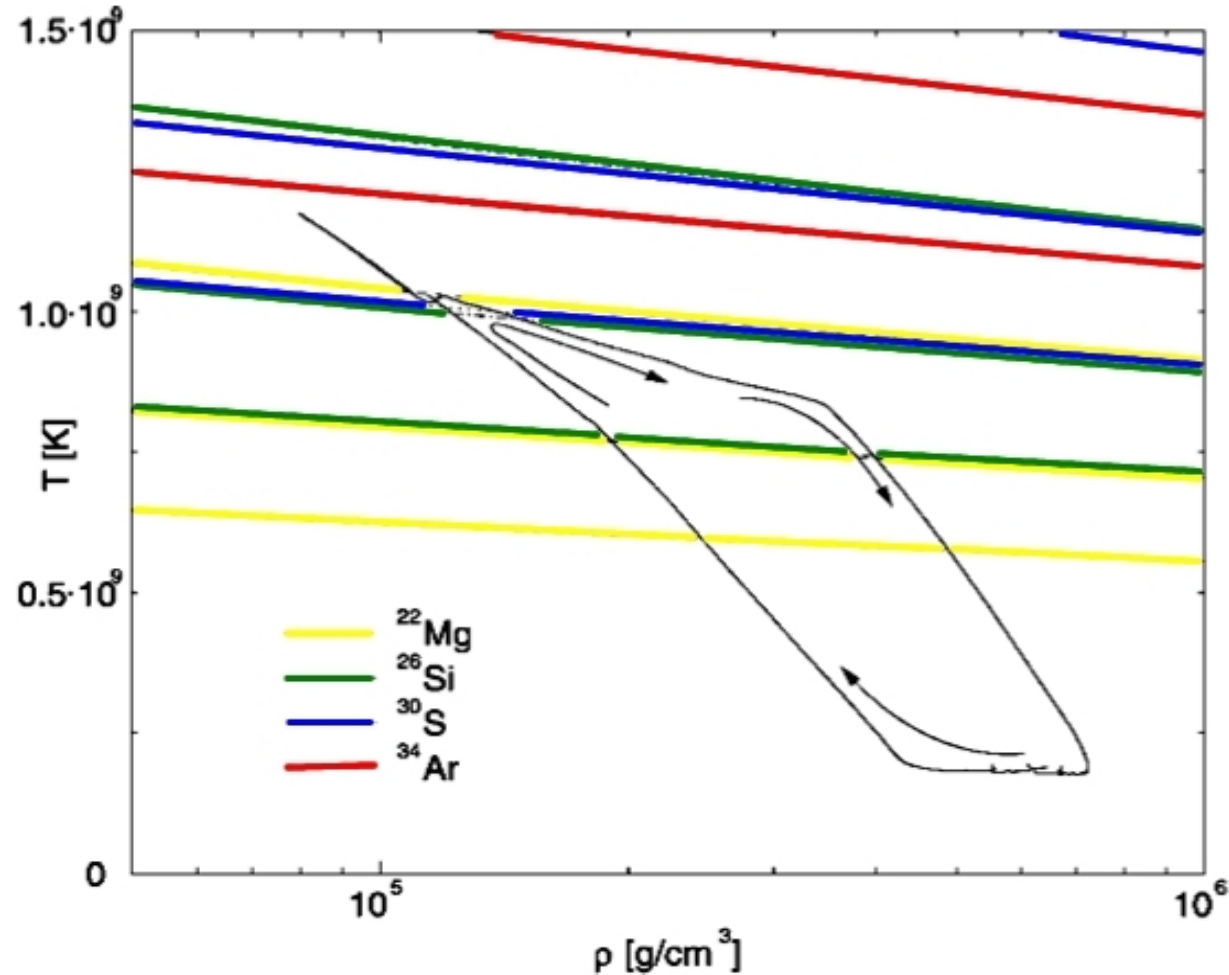


FIG. 2.—Demarcation lines of eq. (1) are plotted thrice with $\Delta(T) = \{10^{-2}, 1, 10^2\}$ and $Y_{\alpha} = 0.125$ for the ^{22}Mg , ^{26}Si , ^{30}S , and ^{34}Ar isotopes. The demarcation line for underestimating $^{34}\text{Ar}(\alpha, p)^{37}\text{K}$ by a factor of 10^2 falls outside the graph. In addition, the solid line shows the thermodynamic trace of the shell conditions during a full burst cycle that is computed in § 4. The arrows indicate the time direction of the cycle.

The road to ^{40}Ca is dim...

- Reaction Flow passes through ^{30}S , ^{34}Ar
- β^+ -decay is too long
- Photodisintegration prevents proton capture
- Temperatures are not high enough for (α, p)
- Are we convinced this model is correct?

$^{30}\text{S}(\alpha, p)^{33}\text{Cl}$ is a waiting point!

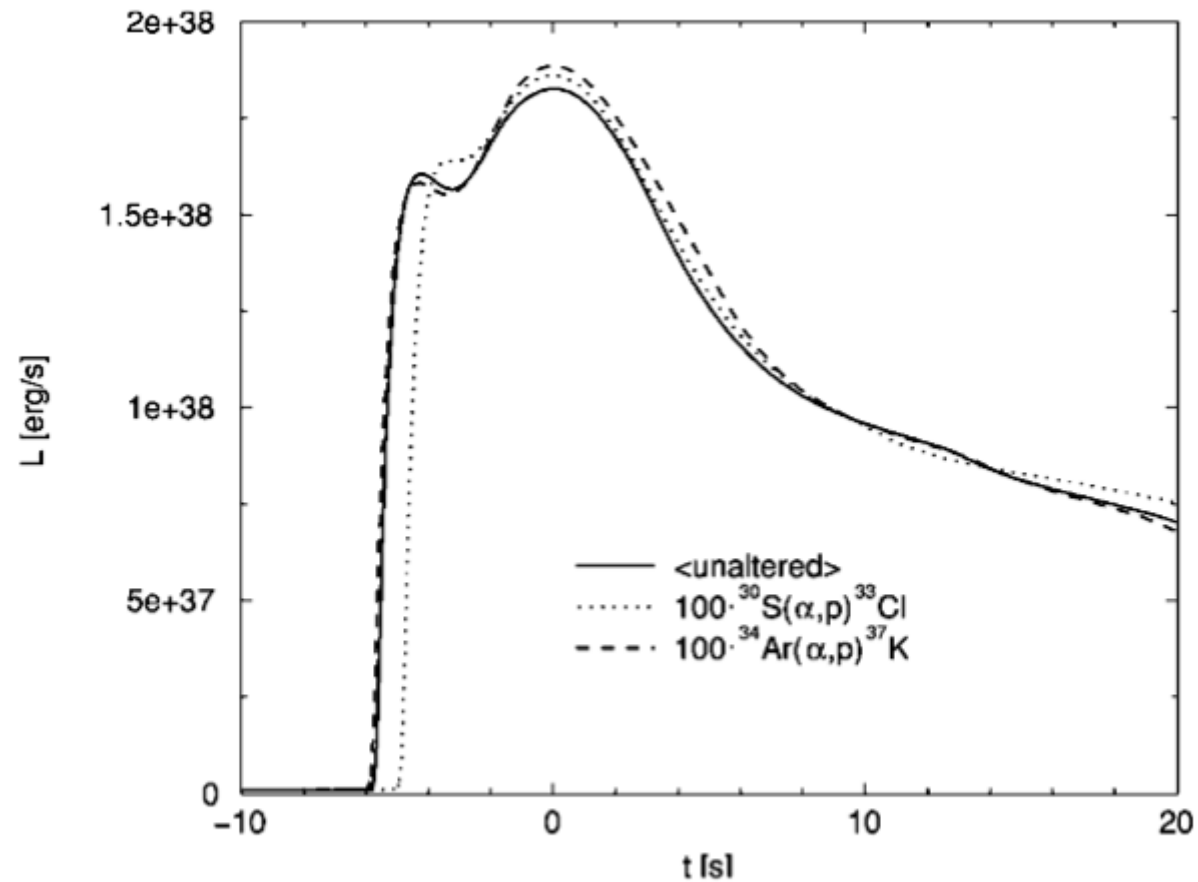
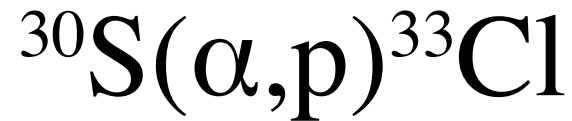


FIG. 3.—Computed luminosity is plotted as a function of time for the three cases. The three luminosity curves have been synchronized to make the second burst peaks coincide.



- $T_{\text{MAX}} = 1 \text{ GK}$ for burst
- Thermonuclear burning can pass waiting point
- Hauser Feshbach statistical model may not apply
 - Excitation Level Densities
 - Dominated by α -cluster resonances
 - $^{18}\text{Ne}(\alpha, \text{p})^{21}\text{Na}$
 - Mirror nuclei show similar behavior ($N_1=Z_2, Z_1=N_2$)
- No experimental data
- Sounds like a thesis

Uncertain Factors

- Models of Convection
- Accretion Rate
- Restrictions of Spherically Symmetric Models
- $^{30}\text{S}(\alpha, p)$ and $^{34}\text{Ar}(\alpha, p)$ reactions rates

Summary

- Double peaked X-Rays bursts poorly understood
- Excellent theoretical postulates
- More experimentation and observation can test the predictions of this theory
- Nuclear physics is important to understanding astrophysical phenomena

Works Cited

- Carroll, Bradley W., and Ostlie, Dale A., *An Introduction to Modern Astrophysics*, Second Edition, Pearson Education, New York, 2007.
- Fisker, J. L., Thielemann, F. K., Wiescher, M. 2004, ApJ, 608, L61.
- Pagel, Bernard E. J., *Nucleosynthesis and Chemical Evolution of Galaxies*, Cambridge University Press, Cambridge, 1997.
- Rolfs, Claus E., Rodney, William S., *Cauldrons in the Cosmos*, University of Chicago Press, Chicago, 1988.

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