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DISCOVERY OF HE 1523-0901, A STRONGLY *r*-PROCESS-ENHANCED METAL-POOR STAR WITH DETECTED URANIUM.

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Subject Headings: early universe – Galaxy; halo – nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: individual (HE 1523-0901)

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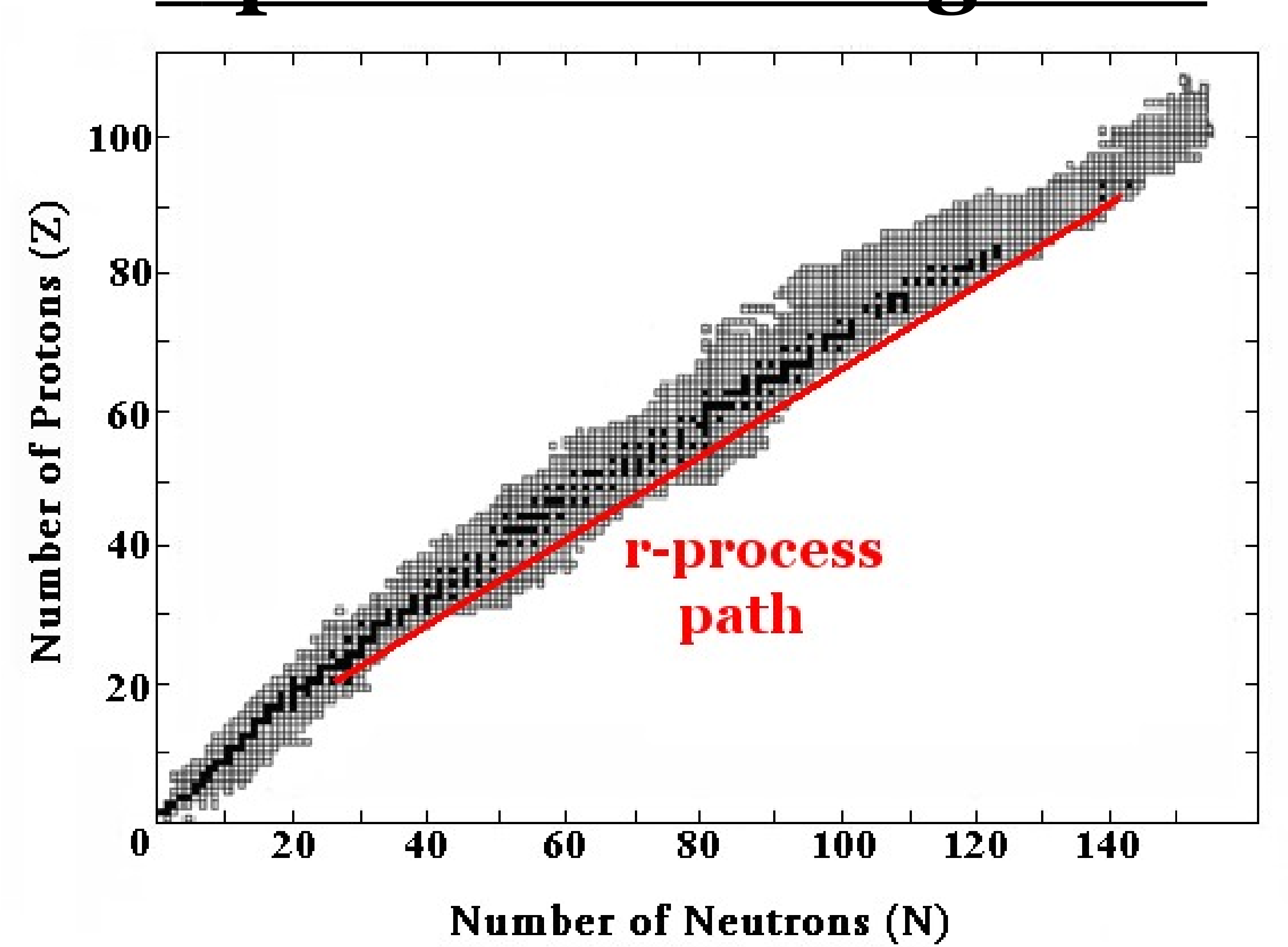
Outline

- HE 1523-0901 has highly unusual abundance ratios
  - r-process-enhanced, metal-poor, Uranium detected
  - Only 2nd observed star of this type
  - ESO Very Large Telescope (Garching, Germany)
- Background on nuclear astrophysics
  - What you need to know to care about this star
- Compare to other Uranium stars
  - Reproduce known data, illustrate uncertainties, history
- Nucleochronometry yields an age of 13.2 Gyr
- Concluding remarks

Radioactive Dating Stars

- Observe abundaces of heavy radioactive elements
  - ^{238}U ($t_{1/2}$ = 4.5 Gyr), ^{232}Th ($t_{1/2}$ = 14 Gyr)
- Quiescent stars cannot synthesize past ^{209}Bi
  - Half of nucleosynthesis past ^{56}Ni is explosive
    - *r*-process, or rapid neutron captures compared to β^- decays
    - All nucleosynthesis past ^{209}Bi
  - Half of nucleosynthesis from ^{56}Ni to ^{209}Bi is thermal
    - s-process, or slow neutron captures compared to β^- decays
- U & Th in a star are at least as old as the star
    - Assume no accretion
- U/Th, U/*r*, & Th/*r* are nuclear chronometers

r-process Burning Path



- Origin of U, Th
  - Models → production ratio → zero age abundances

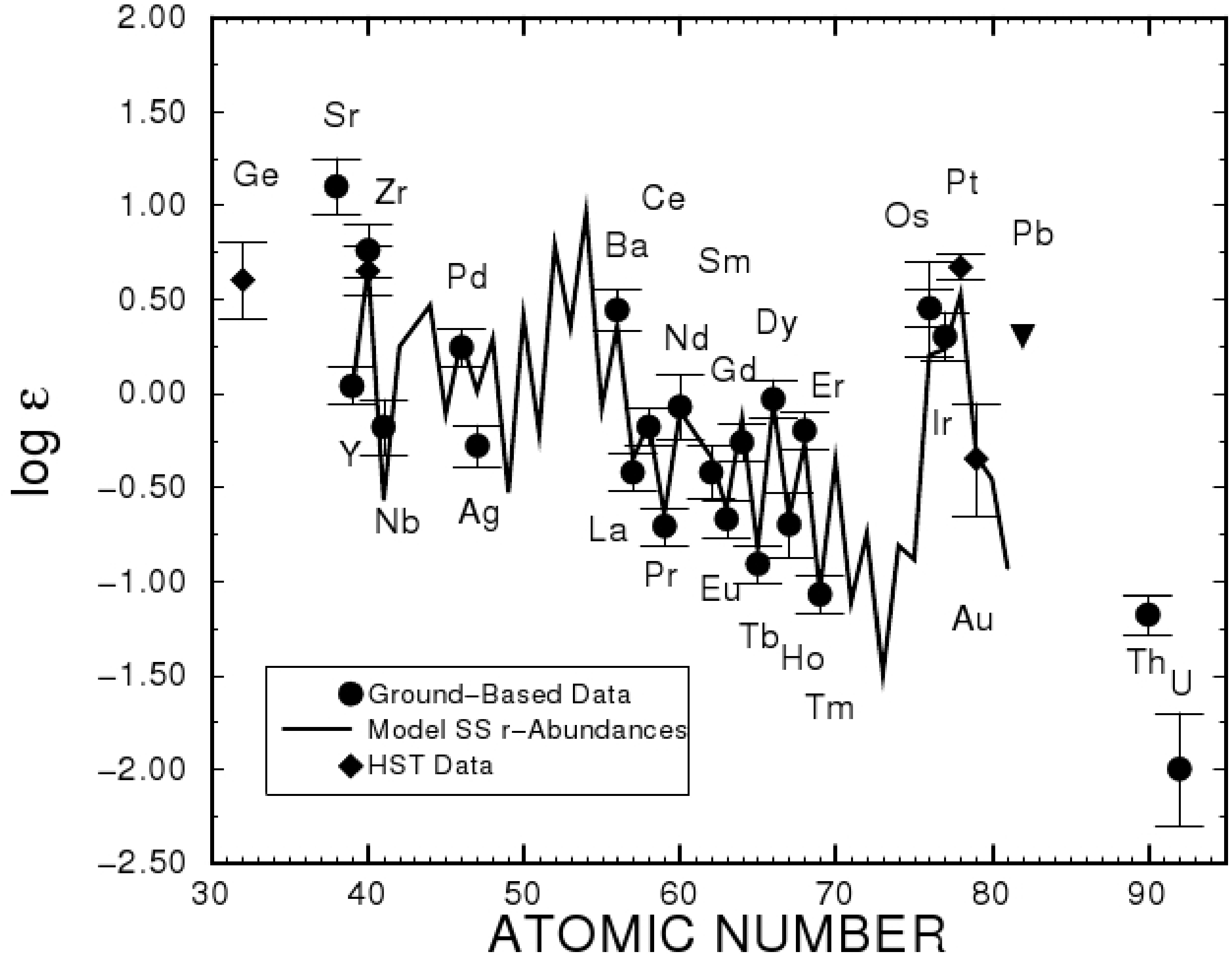
r-process Enhanced? How?

- First stars are made of BBN material
  - 75% H, 25% He, traces of Li
  - First stars explode making *r*-process material
- 2^{nd} generation stars are made of primary nuclei
  - Primary means "can be made from BBN material"
- s-process requires secondary nuclei
  - $^{13}C(\alpha,n)$ [95% of neutrons], $^{22}Ne(\alpha,n)$ [5% of neutrons]
- $\alpha + \alpha + \alpha \rightarrow {}^{12}C$, ${}^{12}C + p \rightarrow {}^{13}C$
  - In **first stars**, He only ignites in core after H exhausted
    - Anywhere there is ^{12}C, there are no protons! (~~Mixing~~)
    - Second gen. stars cannot have ^{13}C initially

Uranium Star (CS 31082-001)

- First *r*-process enhanced, metal-poor U star
    - Observation reported by Cayrel *et al.* (Nature 2001)
- Nuclear dated by Hill *et al.* (A&A 2002)
    - Th/Eu chronometer yields negative / T-Tauri age (< 100 Myr)
        - Large mass separation ^{232}Th and $^{151\text{-}3}$Eu – large uncertainty
        - Th has longer $t_{½}$ than U by factor of 3 – larger uncertainty
    - U/Th used for the first time to date a star: 14.0 ± 2.4 Gyr
        - ^{238}U and ^{232}Th are close in mass
        - Production Ratio (PR) affects this ratio much less than Th/*r*
        - Similar observational parameters
- Schatz *et al.* (ApJ 2002)
    - 15.3 ± 3.2 Gyr age using U/Th ratio

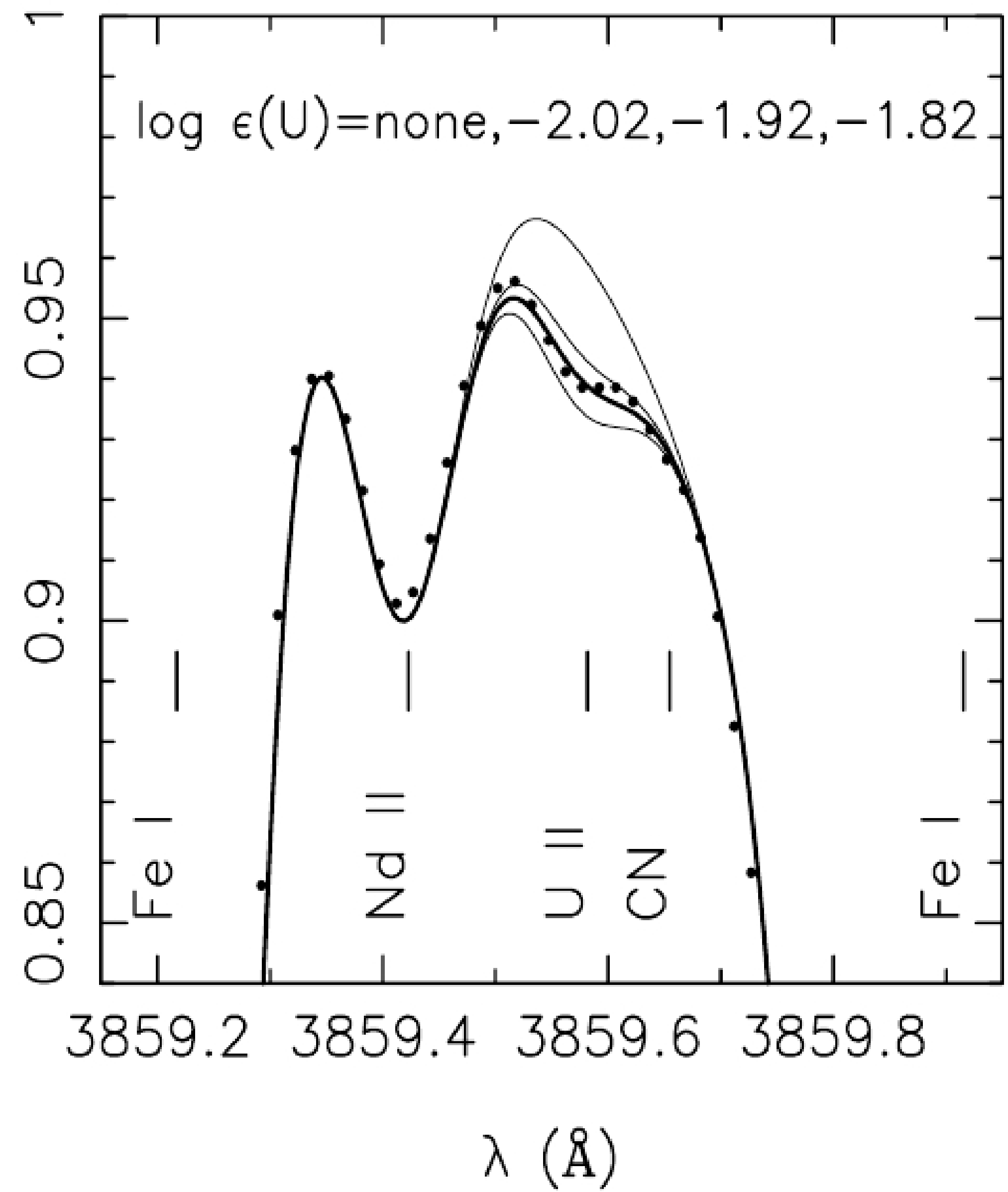
r-process abundances in CS 31082-001



- Long lived *r*-process nuclei match solar abundances
- log $\varepsilon(\mathrm{H})_{\mathrm{solar}} \equiv 12.00$

U II Line in CS 31082-001

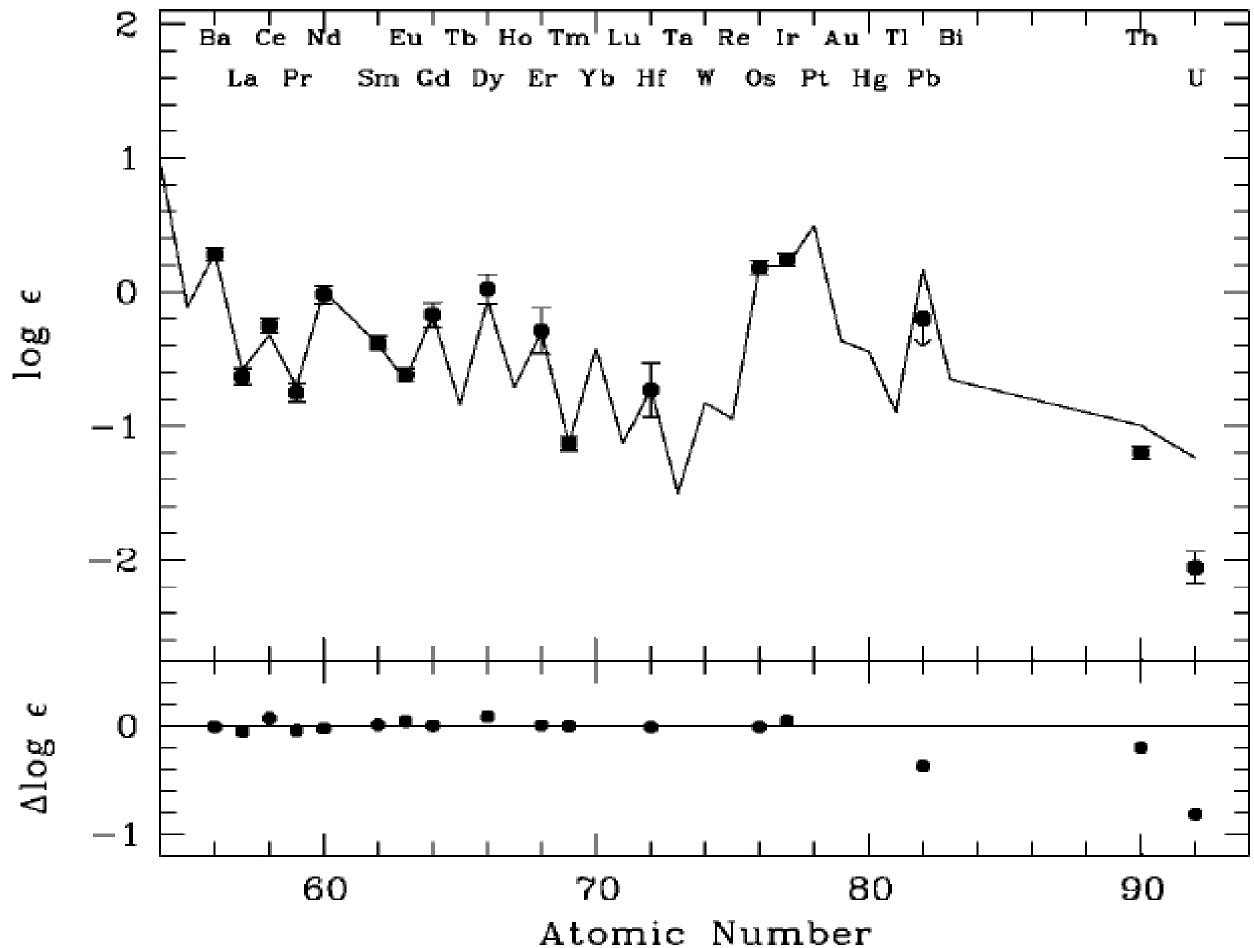
- Strongest U line in optical
  - 3859.6 Å
  - Hill *et al.* 2002
- [Fe/H] = −2.9, T_{eff} = 5200 K
- Best fit: log ε(U) = −1.92
  - log $\varepsilon(U)_{solar}$ < −0.47
- U II line contaminartion
  - Close to CN, strong Fe I wing
  - Low C, N to measure U
    - CS 22892-052 is C rich
      - Sneden *et al.* 1996



Why would a star be carbon poor?

- Carbon comes from $\alpha + \alpha + \alpha \rightarrow {}^{12}C$
- *r*-process material can be made from H, He only
- *r*-process site(s) is/are unknown
  - May not be (only) core collapse SNe
  - SNe progenitors have undergone core He burning
    - This means core-collapse SNe eject ${}^{12}C$
- *r*-process 'only' requires high neutron flux
  - Anywhere high entropy will do the job
  - Could result in ejecta with $Y_C \approx Y_U$
- Uranium stars indicate non-SNe *r*-process site!

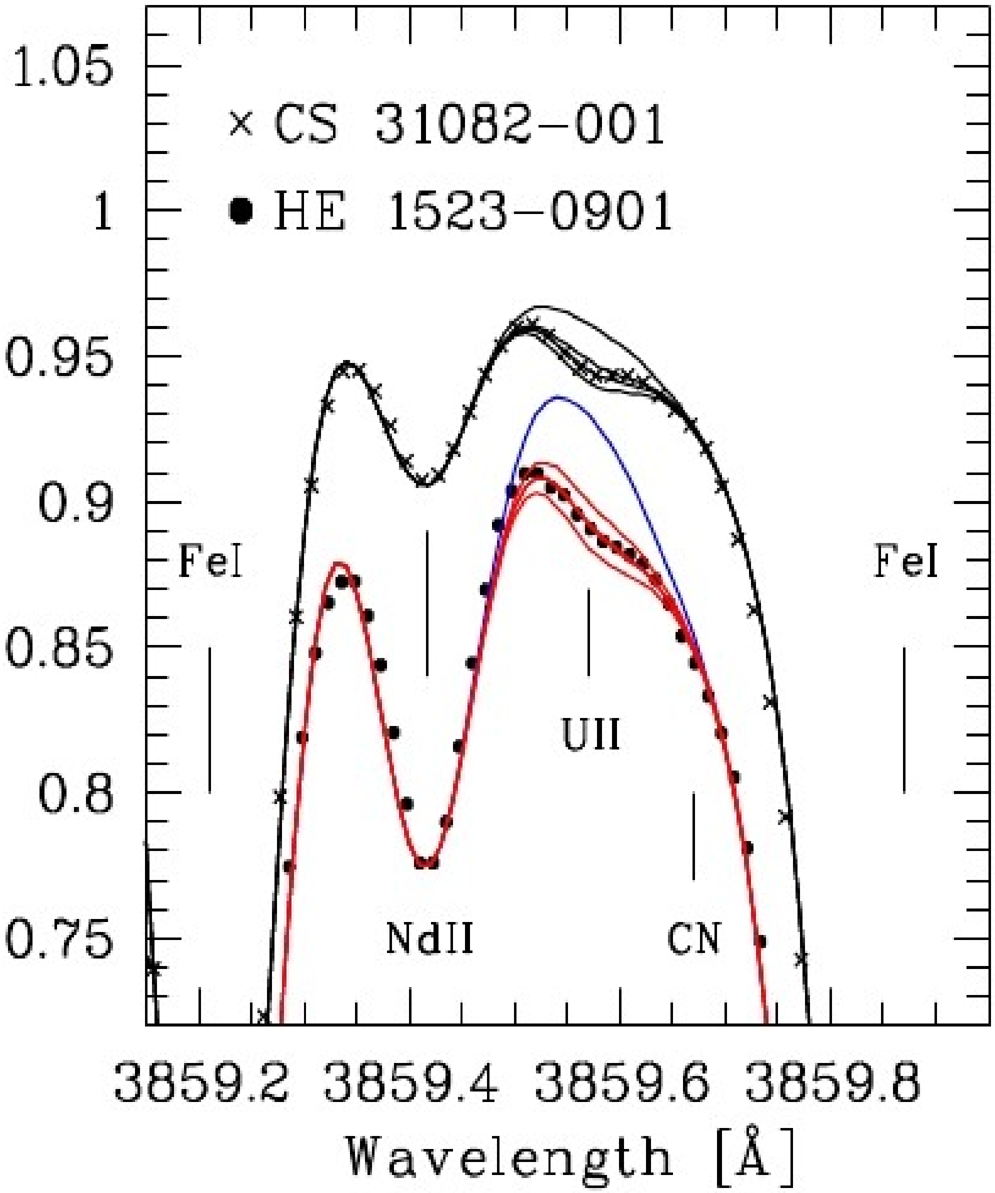
r-process abundances in HE 1523-0901



- Long lived *r*-process nuclei match solar system abundances very well

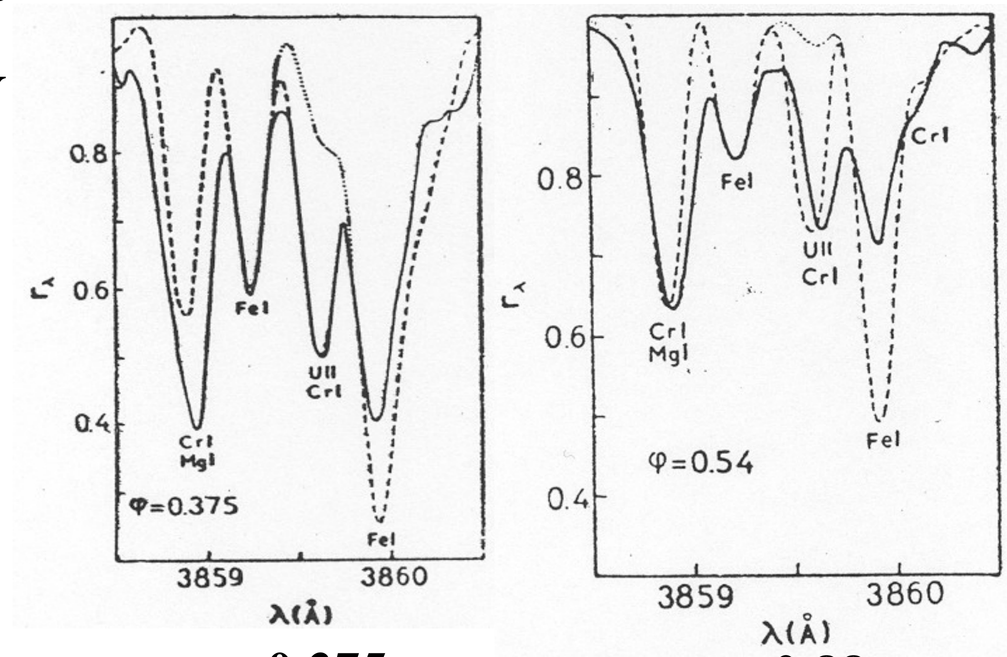
U II Line in HE 1523-0901

- Frebel *et al.* 2007
- [Fe/H] = −2.95
- T_{eff} = 4630 K
- CS 31082-001 (top)
  - Best fit: log ε(U) = −2.15
- HE 1523-0901 (bottom)
  - Best fit: log ε(U) = −2.06



History of CN Line and U Stars

- 3883 Å Cyanogen (CN) Band
  - Dissociation energy 7.7 ± 5 eV
- Observed in solar spectrum
  - R. T. Birge (1924)
- U II Line in Ap Stars
  - Cowley *et al.* (1977)
- Ap Star 73 Draco(nis)
  - I. Kh. Iliev *et al.* (1986)
  - log ε(Fe) = 7.9 ± 3 (within solar), T_{eff} = 8150 K
  - log ε(U) = 4.1, this is HUGE!
    - Look for *recent* *r*-process event



φ=0.375 **φ=0.88**

Period = 20.275 Days

Nucleochronometry of HE 1523-0901

- First observed U stars are young, not metal poor
- Production ratio (PR) assumed affects age
  - Frebel *et al.* calculate ages derived from different models
- Model of atmosphere will affect abundance calc.
- Uncertainties smaller for U (vs. Th) due to $t_{1/2}$
- High resolution spectral data (R = 75,000)
- Other stellar uncertainties
  - Temperature: T_{eff}; Surface gravity: log (g)

Nucleochronometry of HE 1523-0901

X/Y	log(PR)	Age ± Uncert.
Th/Eu	-0.377	9.5 ± 5.6 Gyr
	-0.33	11.7 ± 5.6 Gyr
	-0.295	13.3 ± 5.6 Gyr
Th/Os	-1.15	10.7 ± 5.6 Gyr
Th/Ir	-1.18	12.1 ± 5.6 Gyr
	-1.058	17.8 ± 5.6 Gyr
U/Eu	-0.55	13.2 ± 1.6 Gyr
U/Os	-1.37	12.9 ± 1.6 Gyr
U/Ir	-1.40	13.3 ± 1.6 Gyr
	-1.298	14.8 ± 1.6 Gyr
U/Th	-0.301	12.2 ± 2.2 Gyr
	-0.29	12.2 ± 2.2 Gyr
	-0.256	13.1 ± 2.2 Gyr
	-0.243	13.4 ± 2.2 Gyr
	-0.22	13.9 ± 2.2 Gyr

Calculate Ages From Radioactive Dating

- 13.2 ± 1.8 Gyr for HE 1523-0901
  - First time U/Th, U/*r* & Th/*r* chronometers used in one star
- Using U/Th ratio, may compare to CS 31082-001
  - HE 1523-0901 is youger by 1.5 Gyr
    - Independent of production ratio employed
  - Within age uncertainty, they formed at the same time
    - Corroborated by similar metallicity [Fe/H] ≈ 2.9
- Lower limit for the age of the universe
- Good agreement with *WMAP* 13.7 Gyr for age of universe

Discussion

- High res. stellar spectroscopy is a useful tool
  - Puts constraints on many astrophysical models
  - Tells us how nuclear abundances change with time
- *r*-process-enhanced, metal-poor, U stars interesting
  - Is there a non-SNe r-process site?
  - Are there many other stars of this type?
- Nuclear physics is important to astrophysics

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