Neutron-capture Nucleosynthesis in Relics of the First Galaxies

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Ji et al. 2016
*Nature*, 531, 610
arxiv:1512.01558

Ji & Frebel 2018
*ApJ* 856, 138
arxiv:1802.07272

Ji et al. 2018
*ApJ* accepted
arxiv:1809.02182

Brauer, Ji et al. 2018
*ApJ* submitted
arxiv:1809.05539
Outline

• Ultra-faint dwarf galaxies
• Neutron-capture nucleosynthesis
• UFDs with large amounts of r-process
• UFDs with low neutron-capture elements
• Connection to Milky Way’s halo
History of Milky Way Satellites

Year 1916

Movie by Marcel Pawlowski
No overdensity in 2D

All stars
0.3 x 0.3 sq deg
(∼1/3 the size of the moon)

Yes overdensity in 2+2D

Ret II Stars

Fermilab/Dark Energy Survey
Ultra-faint dwarf galaxies (UFDs)

- Low luminosity ($\sim 300 - 30,000 \, L_{\odot}$)
- Dark-matter-dominated ($M/L > 100$)
- Metal-poor (Mean $[\text{Fe}/\text{H}] < -2$)
- Old (Mean stellar age $13.3 \pm 1 \, \text{Gyr}$)
- Solve the missing satellite problem

The stars in each UFD preserve a short, independent burst of early chemical enrichment with a known environment!

The ideal place to study metal-poor stars. Look at a sample of UFDs!
Light elements in UFDs

A complete homogeneous reanalysis is desperately needed

References here:
Feltzing+09, Norris+10, Gilmore+13, Ishigaki+14, Frebel+16, Ji+16acd, Francois+16, Frebel+10, Koch+08/13, Nagasawa+18, Simon+10, Frebel+14, Roederer+Kirby 14, Chiti+18, Hansen+17, Ji+18

Now with 15 UFDs!
Neutron-capture elements in UFDs

UFDs obviously different than halo stars

Neutron-capture elements are the defining abundance feature of UFDs
Solar System Abundances

s-process: AGB stars
r-process: neutron star mergers (NSMs) and/or supernovae (SNe)

Sneden et al. 2008
Nucleosynthesis in the r-process
Joint Institute for Nuclear Astrophysics 2012

Time: 1.7e-03 s
Temperature: 5.46 GK

r- and s-processes make the same elements but in different ratios

Z (number of protons)

N (number of neutrons)

Video: JINA-CEE Meyer and Surman
Neutron-capture elements in UFDs

Two UFDs are r-process enriched!

The others have very low neutron-capture
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Ret II stars >100x higher neutron-capture element abundances than other UFDs


gray points: Milky Way halo stars

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Ret II stars >100x higher neutron-capture element abundances than other UFDs

A pure r-process pattern! <1% contamination
The Rare and Prolific r-process event in Ret II

- Rate: 1-2 r-process events out of 15 UFDs
  $\rightarrow$ 1 event per $\sim 1000$-2000 CCSNe

Population synthesis: $\sim 1$ event per 1000 CCSNe
GW170817: $\sim 1$ event per $\sim 200$ CCSNe

- Yield: measure $[\text{Eu/H}] \sim -1.3$, estimate gas dilution mass $10^5$-$10^7 \, M_{\text{sun}}$
  $\rightarrow$ $10^{-4.5\pm1} \, M_{\text{sun}} \, \text{Eu}$

NSM simulations: $\sim 10^{-4.3\pm1} \, M_{\text{sun}} \, \text{Eu}$
GW170817: $\sim 10^{-4.7\pm0.5} \, M_{\text{sun}} \, \text{Eu}$

Broadly consistent with a neutron star merger

Ask me about the delay time problem in questions
Other rare and prolific r-process sites

- Magnetorotationally driven jets

- Disk winds in collapsars
  Siegel et al. 2018

- Common-envelope jets supernovae
  Grichener & Soker 2018

- Dark matter-induced implosions
  Bramante & Linden 2016

- And probably many others…

It is very hard to tell the difference with stellar archaeology
All three peaks are made in one r-process event

The solution is NOT adding up ejecta from multiple sites!
But, all three processes can occur in the same site

Models: Eichler et al. 2015, Wu et al. 2016, Nishimura et al. 2015/2017; Ji + Frebel 2018
Neutron star merger components

Heating disk wind
\( \nu \)-driven disk wind

**Polar dynamical**

**Tidal dynamical**

Blue: high \( Y_e \), n-poor, 1st peak elements
Red: low \( Y_e \), n-rich, 2nd-3rd peak elements

Shibagaki et al. 2016

Also see e.g. Metzger 2017
A kilonova-based solution?

- If NSMs enrich metal-poor stars: r-process halo stars and kilonovae have same composition
- Gravitational waves guarantee a NS-NS
- Future KNe $X_{\text{La}}$ distribution should match halo star composition

$X_{\text{La}}$ from GW170817 $\sim 10^{-2\pm0.5}$ (Kilpatrick et al. 2017)
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Neutron-capture elements in most UFDs

What makes this stuff?
- Low but nonzero yield
- $[\text{Sr}/\text{Ba}]$ varies $\sim 2$ dex
- Source of Sr and Ba can be different
- Does NOT dominate n-cap production
Possible origins of neutron-capture elements in most UFDs

- Neutrino-driven wind in CCSNe
  
  e.g., Wanajo 2013

- “Failed” MRD jets
  
  e.g., Nishimura et al. 2015, Moesta et al. 2018

- Spinstars or proton ingestion in Pop III stars
  
  e.g., Cescutti et al. 2013, Clark et al. 2018, Banerjee et al. 2018

- A yet-unknown low-yield r-process source
  
  Halo stars with low n-cap prefer r-process

  * Low but nonzero yield
  * [Sr/Ba] varies ~2 dex
  * Source of Sr and Ba can be different
  * Does NOT dominate n-cap production
What about larger dSphs?

Categorize dwarf galaxies by neutron-capture behavior

Blue: high Sr, high Ba
Orange: low Sr, high Ba
Yellow: low Sr, low Ba

(Dark red: r-process)

Classical dSph references:
Aoki+09, Cohen+Huang 09/10, Fulbright+04, Geisler+05, Hansen+18, Jablonka+15, Kirby+Cohen 12, Norris+17, Shetrone+01/03, Simon+15, Skuladottir+15, Tafelmeyer+10, Tsujimoto+15/17, Ural+15, Venn+12
Neutron-capture element evolution correlates with galaxy stellar and dynamical mass

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Stochastic sampling of rare sources?
 Preferential n-cap loss from small DM halo?
 Time delayed sources?

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Ji et al. 2018
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~Half of r-process enhanced halo stars come from destroyed UFDs

Assuming 10% of UFDs are r-process enhanced
Looking at accreted halo with [Fe/H] < -2.5
“High”-Fe, low-n-cap: the best UFD chemical tag
And they exist!

Roederer+14

~17%

All stars

[Ba/H] < -3.5

~2%

Expect ~2-5% from our model
At this [Fe/H], low-n-capture stars are as rare as r-process enhanced stars

Large (high-res?) spectroscopic surveys needed to look for this!

Brauer et al. 2018
Ji et al. 2018
Summary

• Neutron-capture elements are the defining abundance feature of the faintest dwarf galaxies

• The r-process is dominated by a rare, prolific source: neutron star mergers most plausible

• The origin of neutron-capture elements in most UFDs remains unknown

• Neutron-capture elements encode something about galaxy mass

• Halo stars with extreme neutron-capture elements can be chemically tagged to the faintest building blocks of our MW halo
Extra Slides
Ret II has unusually low Th

Naive application of literature production ratios:
Age = 24.9 ± 2.8 ± 10.3 ± 3.2 Gyr

(stat) (sys, obs) (sys, PR)

More likely explanation: variable initial production ratios
UFD Environment Mitigates Delay Time Problem for NSMs

Single supernova can delay star formation for 25 Myr
Very inefficient star formation

Figure: Bland-Hawthorn et al. 2015
Also see Jeon et al. 2015, Ishimaru et al. 2015, Chiaki et al. 2017, …
Neutron star merger delay time

20% from 10-100Myr

Dominik et al. 2012
Fast-merging neutron stars

Submodel A:
requires binaries to survive
"unstable BB" mass transfer

Safarzadeh et al. 2018
Carbon through Zinc similar to halo stars at [Fe/H] ~ -3

r-process not correlated with light elements

Zinc and MRD Jet SNe

Nishimura et al. 2017 predicts $[\text{Zn}/\text{Fe}] > +1.5$ for MRD Jet SN. Zn chemical evolution in Ret II could constrain the r-process site if we know the dilution mass.
Varying lanthanide fraction