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# A Full Chemical Analysis of the Red Giant in Gaia BH3

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## ABSTRACT

Gaia BH3 is the third black hole that was discovered in the early data release in Gaia DR4 due to the astrometric implication of a dark 33 $M_\odot$ companion of a red giant. The red giant is old, metal-poor, and alpha-enhanced. The possible production mechanisms for this binary system and the initial detection of Eu in this star (Gaia Collaboration et al. 2024) made this red giant companion a prime target to follow-up. Here we present a full chemical abundance analysis based on ∼40 hours of high-resolution spectroscopy from the Tull Coudé Spectrograph on the 2.7m Harlan J. Smith Telescope at McDonald Observatory. With the highest SNR spectrum to date of this star, we confirm the presence of neutron capture elements, including europium, as well as lithium. The star's relatively "normal" chemical fingerprint supports a dynamical formation scenario over isolated binary evolution. We attempt to use the r-process elements detected in this red giant to place an age on this system. These observations lay the groundwork for heavy-element chemical analysis for subsequent black-hole and stellar binaries that will likely be found in Gaia DR4.

## 1. INTRODUCTION

In preliminary Gaia DR4 results, a 33 $M_\odot$ black hole was discovered in a binary with a red giant using Gaia astrometry and the Gaia Radial Velocity Spectrometer (Gaia Collaboration et al. 2024). This unusual system, located in the Galactic halo at 590 pc and part of the ED-2 stream, has an orbital period of 11.6 years.

It is the most massive stellar-origin black hole known, making it a uniquely valuable case for studying hierarchical black hole formation and the possible seeds of intermediate-mass black holes. Its luminous companion is an old metal-poor red giant with [Fe/H] ∼ –2.56, [α/Fe] ∼ 0.43, and [Eu/Fe] ∼ 0.52.

A detailed chemical analysis of this rare system could shed light on how it formed. This system could have formed through isolated binary evolution, where these objects were born together and survived the event that created the black hole. Alternatively, this system could have formed through dynamical capture, where these two objects were later bound through gravitational interactions. The chemical fingerprint of this star may highlight any material transfer from the supernova that created the black hole. Conversely, the stellar chemistry could be that of a typical halo star and promote the idea that this system formed through dynamical capture.

**Table 1.** Stellar Parameters derived from this work

| Parameter | Value |
|---|---|
| $T_{\rm eff}$ | 5416 ± 84 K |
| log $g$ | 3.00 ± 0.04 dex |
| [Fe/H] | -2.27 ± 0.14 dex |
| [α/Fe] | 0.42 ± 0.17 dex |
| $\xi$ | 1.54 ± 0.11 km/s |

Rapid-neutron capture (r-process) elements have strong distinguishing powers among stars (e.g., Manea et al. 2024), and as such the heavy elements of this system can help constrain the formation mechanisms of this system. Further, studying metal-poor stars enhanced with r-process elements can provide important clues about the still-elusive astrophysical site of the r-process.

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## 2. DATA

We obtained 40+ hours of observations of Gaia DR3 4318465066420528000 using the Tull Coudé spectro-

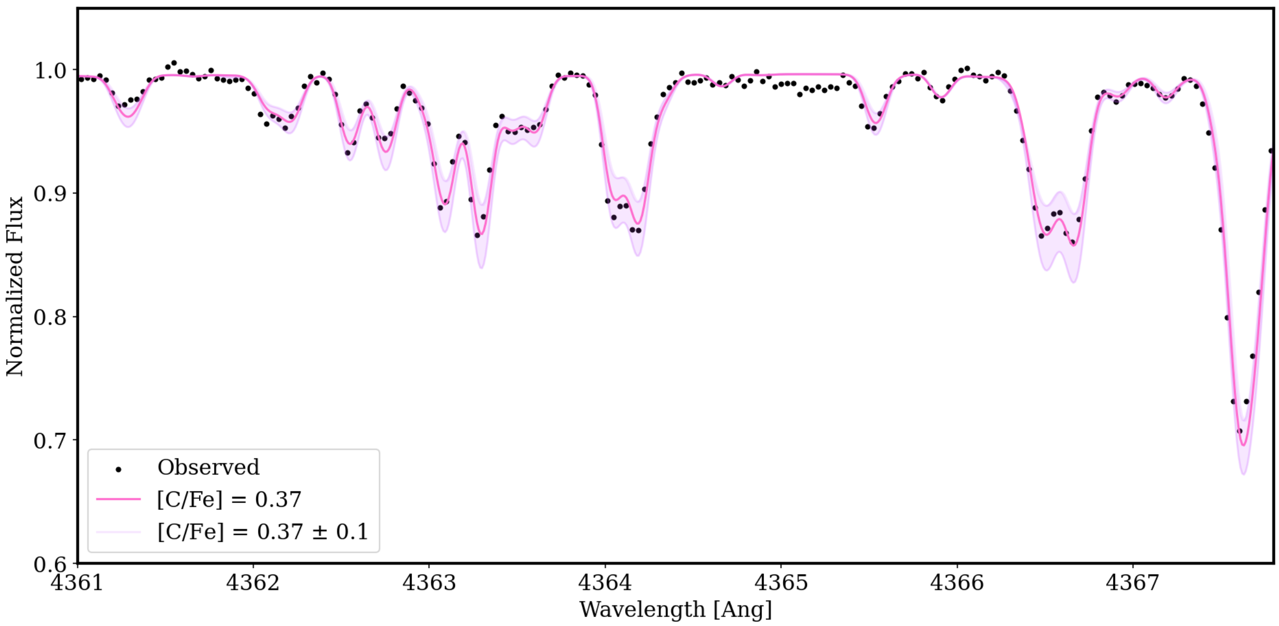


**Figure 1.** We show the observed spectrum of the red giant in Gaia BH3 in black points, with a synthetic spectrum fit to a carbon abundance of [C/Fe] = 0.37 in pink. The purple region shows the [C/Fe] ± 0.1.

graph on the 2.7m Telescope at McDonald Observatory, yielding the highest S/N spectrum of this star to date (S/N $\sim$ 200).

## 3. METHODS

To complete this analysis, we followed the following steps:

- We derived effective temperature and surface gravity photometrically using the G-$K_s$ color and the $K_s$ magnitude, following Mucciarelli et al. (2021) and Casagrande & VandenBerg (2014). Our derived stellar parameters are shown in Table 1.
- Light, alpha, and Fe-peak element abundances were measured with Brussels Automatic Code for Characterizing High accUracy Spectra (BACCHUS) via spectral synthesis and $\chi^2$ minimization (Masseron et al. 2016). BACCHUS uses the radiative transfer code TURBOSPECTRUM (Plez 2012) and the MARCS model atmosphere grid (Gustafsson et al. 2008).
- For r-process elements with weak or blended lines, we synthesized each region using TURBOSPECTRUM.

## 4. ANALYSIS

### 4.1. *Light, $\alpha$, Fe-peak, and s-process elements*

As aforementioned, light, alpha, and Fe-peak element abundances were measured with BACCHUS. For numerous r-process elements, lines were often blended with C features. To illustrate our confidence in our C abundance, we plotted the CH band at $\sim$ 4300Å in Figure 1. In all of our syntheses for the following elements, we varied the carbon abundance by ± 0.3 dex and saw no difference in the respective regions.

We show the lines of a few representative s-process elements in Figure 2. Here we show a yttrium line with our abundance of [Y/Fe] = -0.30, a barium line with our derived abundance of [Ba/Fe] = -0.12, and cerium line with our derived abundance of [Ce/Fe] = 0.20.

To illustrate any chemical abnormalities in this system, we plot this star compared to other halo stars. We show Gaia BH3 (pink star) compared to other halo stars (grey points) and other ED-2 members (pink squares) in Figure 3.

### 4.2. *r- process elements*

For these heavier elements, we use TURBOSPECTRUM (Plez 2012) to carefully synthesize the region around these lines. We show a confident Eu detection ([Eu/Fe] = 0.57) in the left panel of Figure 4. This [Eu/Fe] abundance classifies this star as an r-I neutron-capture star (Beers & Christlieb 2005).

Due to the slight r-process enhancement of this star, the detection of actinide elements like U and Th is unlikely. We show a possible Th detection in the middle panel of Figure 4, likely resulting in an upper limit. In the final panel of Figure 4, we show that there is no clear U detection in this star.

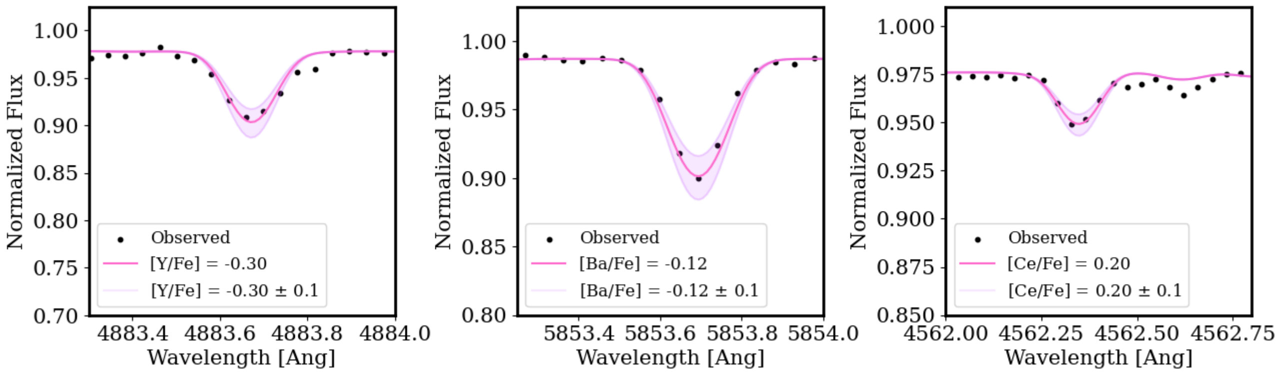


**Figure 2.** We show three lines of different s-process elements, yttrium, barium, and cerium. In all of the panels, the black points are the observed spectrum, the pink lines represent our derived abundances of these respective elements, and the purple region is ±0.1 dex of the abundances.

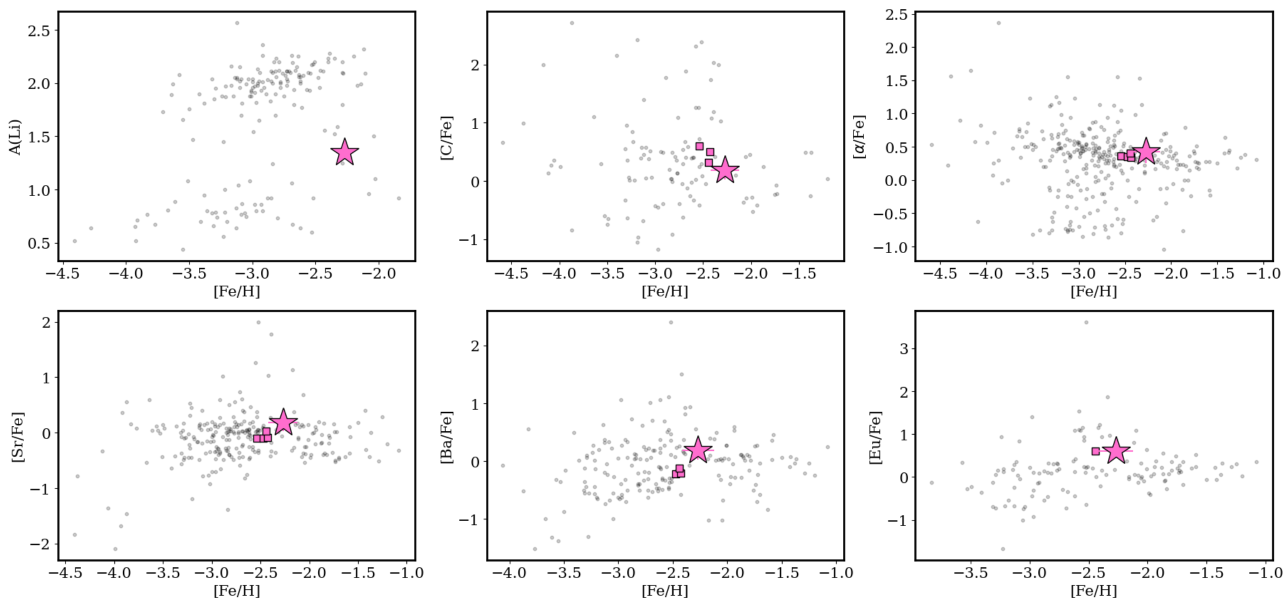


**Figure 3.** Multi-panel comparison of element abundances for the red giant in Gaia BH3 (pink star) with halo stars (grey points; Roederer et al. 2014) and ED-2 stars (pink stars; Dodd et al. 2025). The star lies below the Spite Plateau, with Li consistent with red giant evolution. It is carbon-normal, $\alpha$-enhanced, and has typical Sr and Ba (s-process) abundances. A modest Eu enhancement suggests slight r-process enrichment. Overall, the chemical pattern shows no peculiarities or signs of supernova mass transfer, supporting a dynamical formation scenario over isolated binary evolution.

We attempt to estimate the star's age using nuclear cosmo-chronometry. We use the following equation from Hill et al. (2002):

$$\tau = 46.7\mathrm{Gyr}[\log(\mathrm{Th/Eu})_{\mathrm{o}} - \log(\mathrm{Th/Eu})_{*}] \quad (1)$$

With this equation, we use the production ratio from Schatz et al. (2002) and our Th and Eu abundances to derive an upper limit age of 11.66 ± 5.6 Gyr. Within errors, this is in agreement with the isochrone age of 13.4 ± 1.6 Gyr found in Dodd et al. (2025).

## 5. CONCLUSIONS

Gaia BH3 is the third black hole discovered with Gaia astrometry, in a binary system with a red giant. This star is old, metal-poor, alpha-rich, and r-process enhanced. Here, we present a full chemical analysis of the red giant in Gaia BH3. Given the chemical normalcy of the red giant, we support the interpretation that Gaia BH3 likely formed via dynamical interactions rather than isolated binary evolution (e.g, El-Badry 2024). With a europium abundance of [Eu/Fe]=0.57±0.15, the star qualifies as a mildly r-process enhanced (r-I) star.

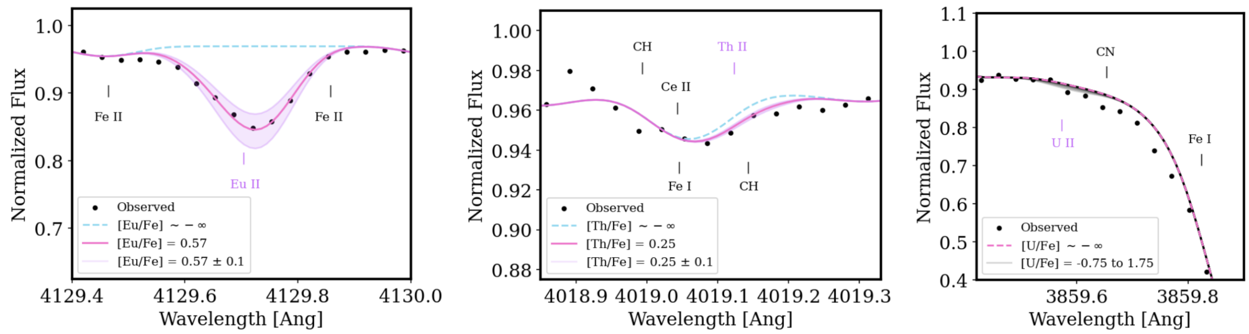


**Figure 4.** Left: We show the observed spectrum of the red giant in Gaia BH3 in black points, with a synthetic spectrum fit to an Eu abundance of [Eu/Fe] = 0.57 in pink. The purple region shows the [Eu/Fe] $\pm$ 0.1. Middle: We show the observed spectrum of the red giant in Gaia BH3 in black points, with a synthetic spectrum fit to an Th abundance of [Th/Fe] = 0.25 in pink. The purple region shows the [Th/Fe] $\pm$ 0.1. This figure highlights the possibility of a Th detection at this line. Right: Observed spectrum (black points) compared to a synthesized spectrum with [U/Fe] $\sim -\infty$ (pink). Grey curves show synthetic spectra from [U/Fe]=-0.75 to 1.75 in 0.1 dex steps. No uranium feature is clearly detected. The nearby Fe I line at 3859.91 Å appears saturated, complicating the measurement of the U II 3859 Å line.

While the lack of actinides limits age dating via cosmochronometry, the system—and the ED-2 stream more broadly—offers a valuable testbed for probing the astrophysical site of the r-process.

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