Red Supergiants in M31: Investigating Binary Candidates in Cluster and Field Environments

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Introduction

Massive stars shape galaxy evolution through radiation, stellar winds, and supernovae. Evolved Helium burning (HeB) stars, and red supergiants (RSGs) in particular, provide key constraints on massive star evolution, mass loss, and Type II supernova progenitors, while binary interactions can significantly alter their evolution. Using photometry from the Panchromatic Hubble Andromeda Treasury (PHAT) survey and the Andromeda Project (AP) cluster catalog, we identify HeBs and RSGs members of M31 clusters. Here we focus on the RSG populations and compare cluster and field populations, compare to RSG samples from the literature, and explore binary star companions through UV excess emission.

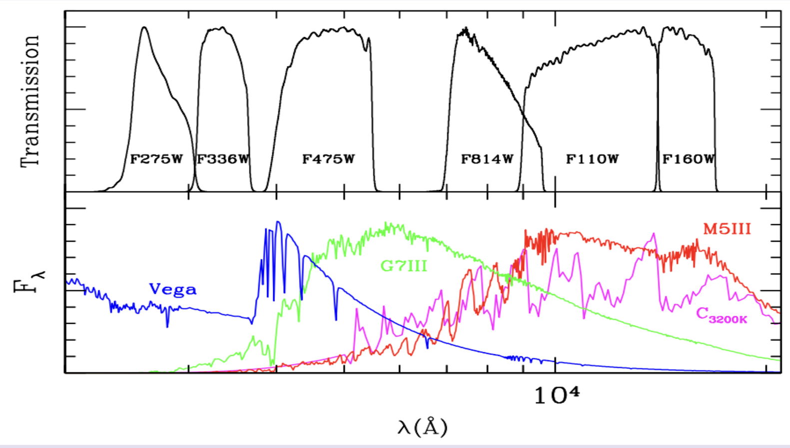

Figure 1. Relative transmission of the PHAT filters as a function of wavelength (top), with representative stellar spectra shown below, including Vega, G7III, M5III, and a carbon star (bottom)[2].

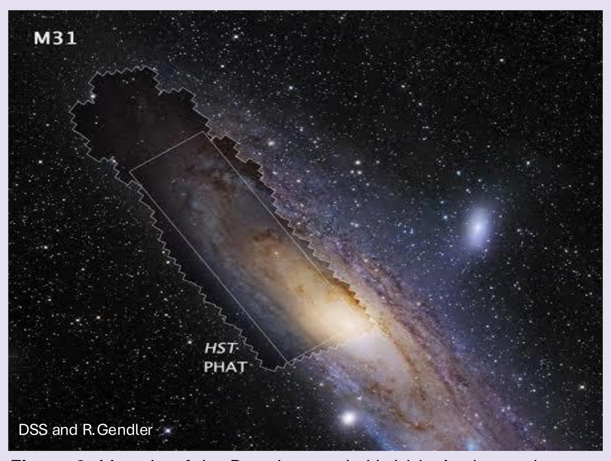

Figure 2. Mosaic of the Panchromatic Hubble Andromeda Treasury (PHAT) survey footprint across the disk of M31.

Cluster Helium Burning (HeB) Star Selection

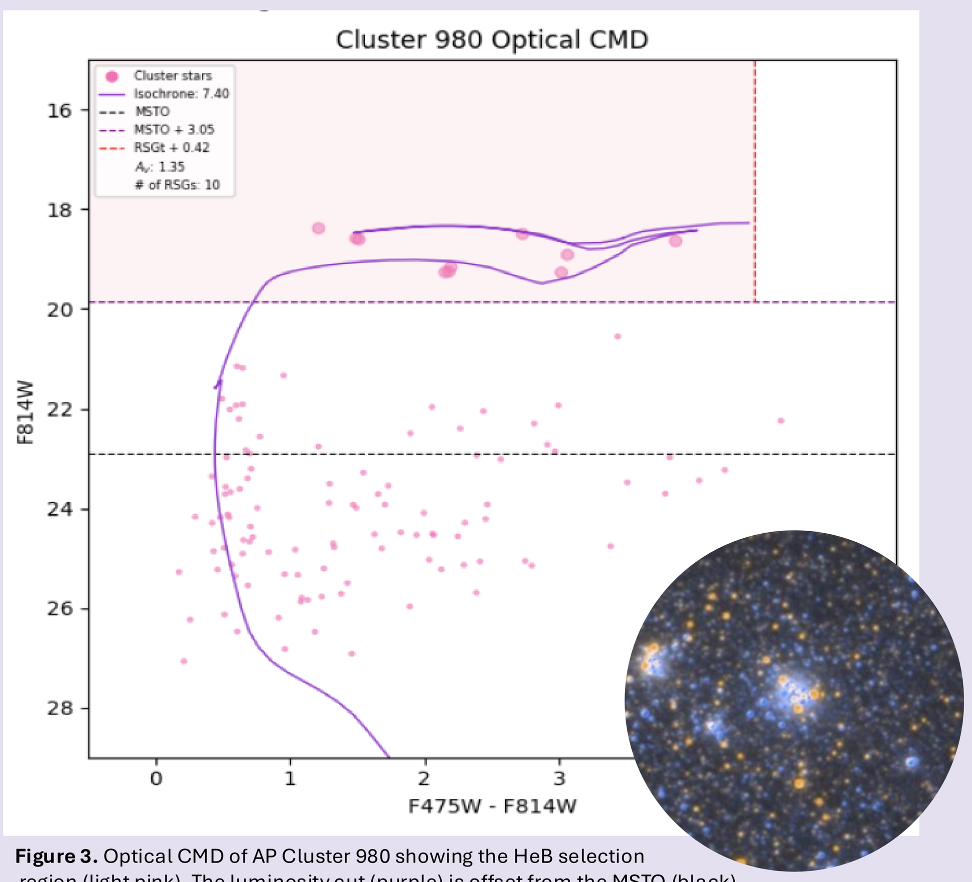

Figure 3. Optical CMD of AP Cluster 980 showing the HeB selection region (light pink). The luminosity cut (purple) is offset from the MSTO (black), while the color cut (red) is based on the RGB tip. Boundaries are derived from age-matched Padova solar-metallicity isochrones (light purple) [3][5]. Cluster stars are shown in pink.

- Identifying evolved HeB stars that are members of star clusters provides valuable age and extinction constraints for these post-main sequence populations.
- Cluster membership was assigned to PHAT[8] stars that lie within the AP cluster aperture[4]. PHAT photometry was filtered according to S/N only (>4 in F475W & F814W); the survey's GST quality cuts on sharpness and crowding are too restrictive for clusters.
- HeB candidates were selected according to their location in the optical CMD (F475W-F814W vs. F814W) relative to best fit Padova isochrones[3][5].
- HeB stars were required to be brighter than the main-sequence turn-off (MSTO) and bluer than the RGB-tip boundary, with boundaries adjusted with age to balance completeness and contamination (see Figure 3).
- HeB matching was conducted over 1506 total clusters with log(age/yr) ≥ 8.0 to focus on massive-star RSGs and reduce RGB contamination.

Results

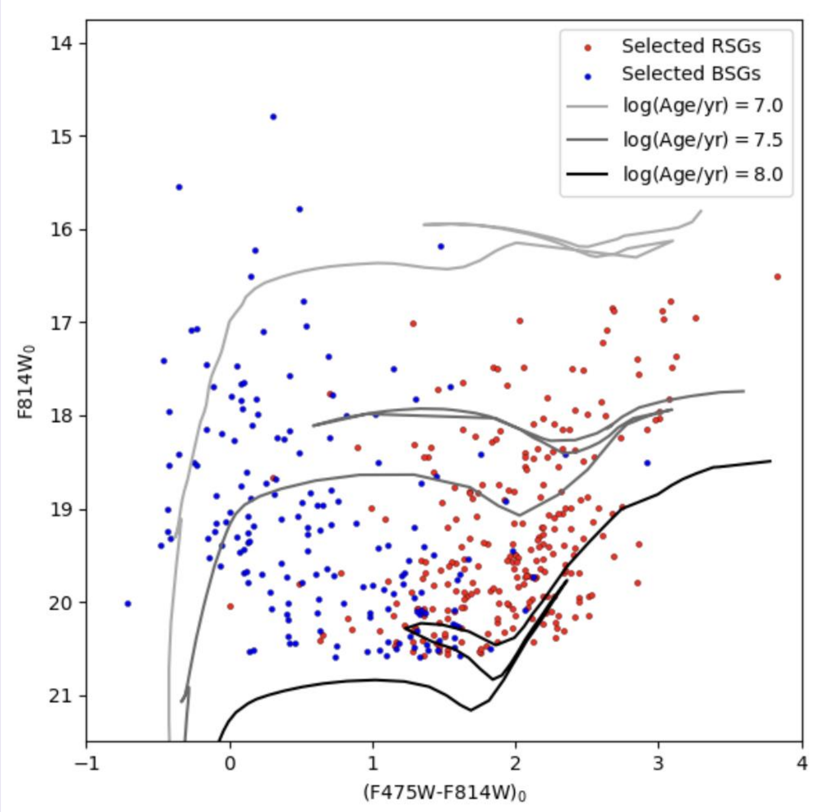

Figure 4. Dereddened optical color-magnitude diagram (CMD) of cluster selected HeB stars. RSGs are indicated in red and BSGs in blue. Padova isochrones[3,5] of log(age/yr) = 7.0,7.5, 8.0 are over plotted for reference.

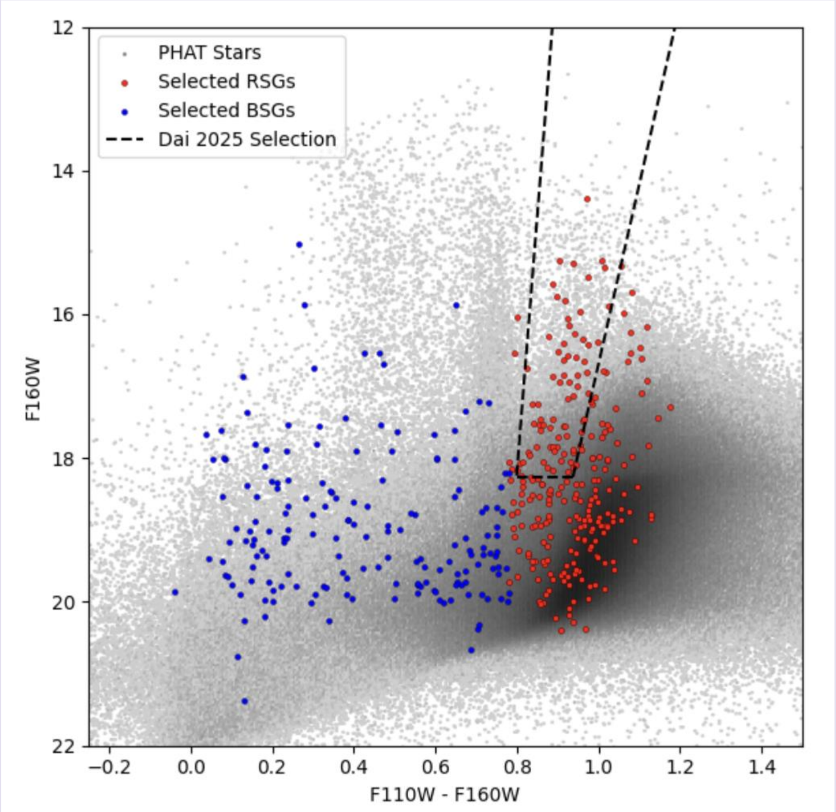

Figure 5. Infrared CMD of PHAT stars (gray) and CMD-selected HeB stars, with RSGs shown in red and BSGs in blue. The dashed lines show the RSG selection criteria from Dai et al. (2025)[1], illustrating the difference between our broader selection and the more restrictive criteria used in their RSG catalog.

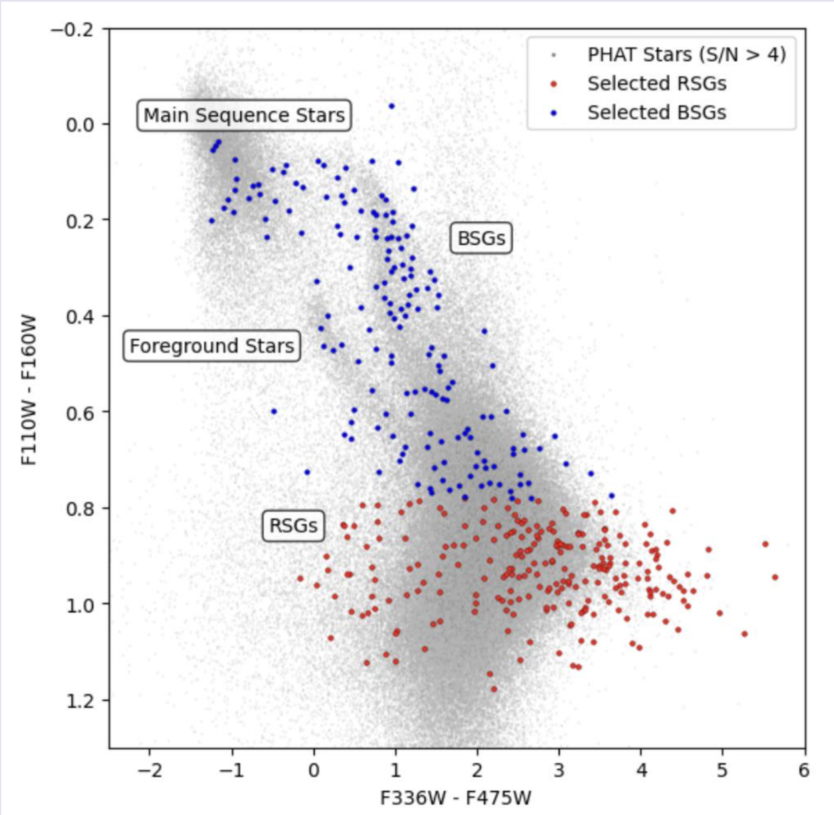

Figure 6. Color-color diagram of PHAT stars (gray) and CMD-selected HeB stars, with RSGs shown in red and BSGs in blue. Main-sequence stars, foreground stars, BSGs, and RSGs are labeled to show the separation between the major stellar populations.

Cluster RSG Sample:

- Identified 424 HeB stars across 237 clusters, including 252 RSGs and 170 BSGs.
  - This sample is shown in the dereddend optical CMD, the NIR CMD, and the color-color plots above. (Figures 4-6)
- RSGs and BSGs were separated using F110W-F160W color, with RSGs defined as F110W-F160W ≥ 0.78; YSGs may contaminate both populations.
- RSG-hosting clusters span log(age/yr)=6.60-8.00, with 58% of RSGs in the oldest bin (7.75-8.00).
  - We calculate the RSG production efficiency according to the full cluster population. (Total mass $=5.05 \times 10^5\ M_\odot$; see bottom of panel Figure 8)

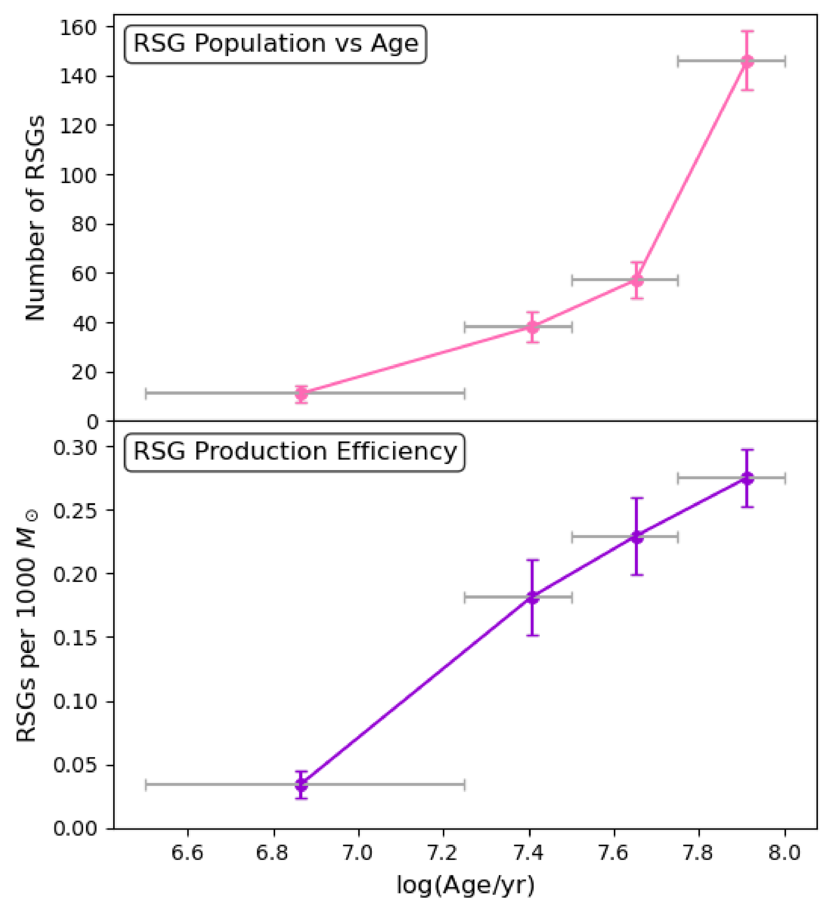

Figure 8. RSG population properties as a function of cluster age for the CMD-selected cluster RSG sample. The top panel shows the number of RSGs and the bottom panel shows the RSG production efficiency per unit cluster mass. Points show the mean cluster age within each age bin with Poisson uncertainties, and grey error bars show bin width.

PHAT-wide RSG Sample:

- RSGs were selected using NIR CMD criteria (Figure 5) with an additional optical-NIR cut to reduce AGB contamination, adopted by Dai et al. (2025).
- GST optical and NIR quality cuts were applied, while no UV GST cuts were imposed (compared to GST cuts in UV bands used by Dai et al. (2025)) to preserve completeness and avoid crowding biases.

Selection Comparison:

- The PHAT-wide selection identifies 5,188 RSGs, with 99 associated with clusters, compared to 252 RSGs identified by our cluster CMD selection.
- The smaller Dai et al. (2025) catalog contains 2,612 RSGs, including 81 cluster-associated RSGs.
- Differences between the PHAT-wide and Dai et al. samples primarily reflect photometric/GST quality cuts, while differences between the cluster CMD and PHAT-wide samples reflect different RSG selection criteria.
- Our PHAT-wide selection recovers a more complete RSG population at older cluster ages, enabling a more robust comparison of cluster and field environments.

Table 1. Summary of RSG samples.

	Number of RSGs	Number of Clusters
Cluster RSGs	252	149
PHAT-wide RSGs: Clusters	99	82
PHAT-wide RSGs: All	5188	···
Dai+25 RSGs: Clusters	81	69
Dai+25 RSGs: All	2612	···

Binary Fraction

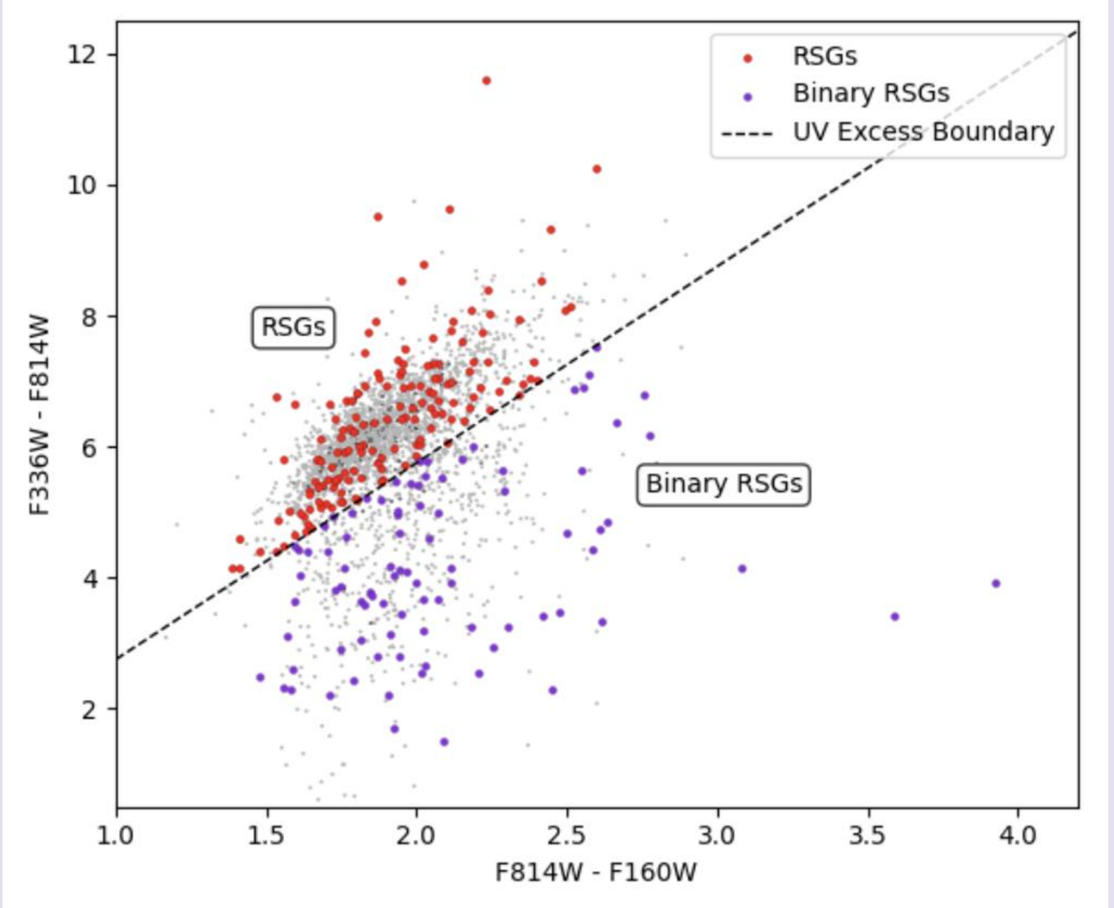

Figure 9. Color-color diagram of CMD-selected RSGs showing the UV-excess binary candidates. Single RSGs are shown in red and binary candidates in purple. The PHAT-wide RSG sample is shown in grey for comparison. The dashed line marks the boundary used to identify UV excess and is inspired by the UV excess plots of Dai et al. (2025).

- UV excess can reveal hot companions to cool RSGs, which contribute relatively little UV flux themselves[1][7].
- Candidate binaries were identified using the F336W−F814W vs. F814W−F160W color-color criterion inspired by Dai et al. (2025).
- Required F336W S/N > 4 to ensure reliable UV detections.
- We use F336W only because F275W is substantially shallower, and requiring F275W detections would bias the sample toward brighter UV sources.
- UV excess is consistent with the presence of a main-sequence companion with a mass of 3–5 $M_\odot$ or greater.
- The higher binary-candidate fraction among cluster-associated RSGs provides a test of whether stellar environment influences the observed binary properties of RSGs.

Table 2. Binary-candidate fractions for the PHAT RSG samples.

Sample	Binary Fraction (%)
Cluster RSGs	25.79
PHAT-wide RSGs: Clusters	25.3
PHAT-wide RSGs: Field	11.6

The binary-candidate fraction is **2.18× higher** for cluster RSGs than field RSGs (25.3% vs. 11.6%).

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