SPITZER SPACE TELESCOPE EVIDENCE IN NGC 6791: NO SUPER MASS LOSS AT SUPERSOLAR METALLICITY TO EXPLAIN HELIUM WHITE DWARFS?

JACCO TH. VAN LOON, MARTHA L. BOYER, AND IAIN MCDONALD

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ABSTRACT

We use archival Spitzer Space Telescope photometry of the old, supersolar-metallicity, massive open cluster NGC 6791 to look for evidence of enhanced mass loss, which has been postulated to explain the optical luminosity function and low white dwarf masses in this benchmark cluster. We find a conspicuous lack of evidence for prolificity of circumstellar dust production that would have been expected to accompany such mass loss. We also construct the optical and infrared luminosity functions, and demonstrate that these fully agree with theoretical expectations. We thus conclude that there is no evidence for the mass loss of supersolar metallicity red giants to be sufficiently high that they can avoid the helium flash at the tip of the red giant branch.

Subject headings: infrared: stars — open clusters and associations: individual (NGC 6791) — stars: evolution — stars: luminosity function, mass function — stars: mass loss — stars: Population II

Online material: color figures

1. INTRODUCTION

Low-mass stars in galactic globular clusters lose ~20% of their mass during the ascent of the first red giant branch (RGB; Dupree et al. 2007; Origlia et al. 2007; McDonald & van Loon 2007), offering a partial explanation for the blue extent of the core-helium-burning horizontal branch (Rood 1973). It has been argued recently that in the old (8 Gyr), supersolar-metallicity (Z = 0.05), massive open cluster NGC 6791, at least 40% of RGB stars experience higher rates of mass loss; this would lead to their departure from the RGB before the helium flash, resulting in undermassive helium white dwarfs (Castellani & Castellani 1993; Hansen 2005; Kalirai et al. 2007). If true, this would have important implications for the white dwarf populations produced in metal-rich stellar systems, and for the mass return into the interstellar medium of such systems—which include giant elliptical galaxies and the bulges of spiral galaxies. Bedin et al. (2008), on the other hand, propose an alternative explanation for the white dwarf properties in NGC 6791 without the need for enhanced RGB mass loss.

We investigate the evidence for super mass loss on the RGB of NGC 6791 by looking for circumstellar dust that may form in the winds from cool RGB stars (e.g., Gehrz & Woolf 1971; Origlia et al. 2007) in archival Spitzer Space Telescope infrared (IR) images, and by comparing the IR and optical luminosity functions with model predictions.

2. SPITZER PHOTOMETRY OF NGC 6791

The observations of NGC 6791 presented here were intended for James Webb Space Telescope photometric and astrometric calibration (Diaz-Miller 2007); we obtained the data from the Spitzer Space Telescope (hereafter Spitzer; Werner et al. 2004) public archive. The observations were made with the Spitzer Infrared Array Camera (IRAC; Fazio et al. 2004) on 2005 June 14 UT. The image maps cover ≈20′ × 15′, with 3.6 and 5.8 μm mosaics offset to the northwest from the cluster center by ≈8′ and by ≈3′ at 4.5 and 8 μm. The region around the cluster is displayed in Figure 1. High dynamic range mode had been implemented to prevent saturation of brighter sources (1 s exposures) while maintaining a high signal-to-noise ratio on fainter sources (26.8 s exposures), and observations had been made with an eight-position cycling dither pattern to build redundancy against outliers and artifacts.

Raw data were processed with Spitzer Science Center (SSC) pipeline version S14.0.0. We corrected the Basic Calibrated Data images for array distortions and mosaicked the resulting images with the SSC Legacy MOPEX software version 16.2.1 (Makovoz & Marleau 2005), which includes background matching to minimize pixel offsets in overlapping regions of the mosaics and eliminates cosmic rays and other outliers.

We carried out point-spread function photometry using the DAOphot II photometry package (Stetson 1987). Sources at least 4 σ above the background were extracted. A sharpness cutoff helped eliminate extended sources and remaining outliers. A pixel-phase-dependent photometric correction was applied to the 3.6 μm fluxes (Reach et al. 2005). The flux estimates are color corrected using a 5000 K blackbody, as specified in the IRAC Data Handbook, version 3.0. Zero magnitudes were taken from the same reference, and flux uncertainties include both the DAOphot errors and calibration errors (Reach et al. 2005). False-star tests indicate that the catalog is complete to at least 90% in the core of the cluster down to [3.6] = 17.5 mag and [8] = 16.5 mag.

3. CLUSTER MEMBERSHIP

Proper motions have been measured for many stars in and around NGC 6791 (Monet et al. 2003; Zacharias et al. 2004; Dias et al. 2006). We designate a star a proper-motion nonmember if the absolute proper motion is >20 mas yr⁻¹ in the Monet et al. (2003) catalog, >14 mas yr⁻¹ in the Zacharias et al. (2004) catalog, or its membership probability was set zero in the Dias et al. (2006) catalog. Figure 2 displays the resulting selection of possible members (top panels) and proper-motion nonmembers (bottom panel).
The figure illustrates the choice of selection criteria for the Monet et al. (2003) and Zacharias et al. (2004) catalogs, which are based on the clearly defined clump of stars with small proper motions (possible members) compared to the much more widely distributed foreground population. The Dias et al. (2006) selection criteria include a positional element. Note that if a star was excluded as a member by any one of these works it is labeled a nonmember in all of the bottom panels of Figure 2.

The proper motion nonmembers are identified with crosses in the Spitzer [3.6], [3.6] – [8] color-magnitude diagram (Fig. 3). This eliminates for instance the very brightest star (star 2240 in Stetson et al. 2003) and the bright very red star at [3.6] = 9.7 mag, [3.6] – [8] = 2.4 mag (star 2349 in Stetson et al. 2003). Objects in the faint, red corner of the diagram are background galaxies; slightly extended objects with similar colors are prominent on the Spitzer images. As expected for galaxies, these objects are spread uniformly across the images.

To eliminate field stars with no or ambiguous proper-motion information, a further criterion is applied on the basis of the optical V, B – V diagram (Fig. 4; using data from Stetson et al. 2003): the main sequence, RGB, and red clump (around V = 14.6 mag, B – V = 1.35 mag) of NGC 6791 are well separated from the bulk of the foreground main-sequence stars. In our subsequent analysis we keep all remaining possible cluster members that have proper-motion information and photometry in all Spitzer IRAC bands and the V band, and that are located within 0.1° projected distance from the cluster center (290.23°, +37.77°).

### 4. EVIDENCE FOR CIRCUMSTELLAR DUST EMISSION

In the absence of longer wavelength data, [3.6] – [8] is the most sensitive Spitzer color to the presence of circumstellar dust.
Dust causes a reddening of this color, first, due to emission at 8 μm, and second, due to extinction at 3.6 μm if the dust envelope is very optically thick. The RGB in NGC 6791 is surprisingly narrow in [3.6] − [8] color (Fig. 3) down to at least [3.6] = 13.5 mag, i.e., more than 4 magnitudes below the RGB tip. Compared to the distribution mirrored around the peak (Fig. 5), at [3.6] − [8] = −0.07 mag, there are 14 out of 72 stars (19% ± 5%) that are redder than expected from a distribution which is symmetric in color. Not only is this but a small fraction; the colors are also only marginally red, with Δ([3.6] − [8]) < 0.1 mag for all but one with Δ([3.6] − [8]) ≈ 0.22 mag. The latter is at the faint end of this RGB selection; indeed, there is no sign of the brightest stars being more likely to show an IR excess as observed, e.g., in ω Centauri (Boyer et al. 2008).

The fraction of dusty stars along the upper 4.5 mag of the RGB in NGC 6791 may be compared with that in the globular cluster 47 Tuc (Origlia et al. 2007). There, ~340 stars are counted in the central part of 47 Tuc, among which 90 are dusty (26%). In the outskirts of 47 Tuc, there are ~160 stars, among which nine are dusty (6%). These statistics may be affected by blending in the central part and field star contamination in the outskirts. Nonetheless, there is no evidence for an abnormally high fraction of dusty stars in NGC 6791 despite an order-of-magnitude higher metal content than in 47 Tuc.

Following Groenewegen (2006) Δ([3.6] − [8]) = 0.1 mag corresponds to a mass-loss rate of (1−2) × 10^{-8} M_☉ yr^{-1} for an M-type star with aluminum-oxide or silicate dust and a luminosity L = 3000 L_☉, wind speed v = 10 km s^{-1}, and dust-to-gas mass ratio ρ = 0.005. In the extreme case of an M10-type star with pure aluminum-oxide dust the corresponding mass-loss rate is nearly 5 × 10^{-8} M_☉ yr^{-1}, but to our knowledge no such RGB star exists. The mass-loss rate scales approximately as M ∝ v_L/υ (van Loon 2000). For a dust-driven wind one expects the dust-to-gas ratio in the metal-rich stars of NGC 6791 to be higher by a factor ~2.5, and the wind speed by a factor ~1.6 (Marshall et al. 2004). The luminosity range along this part of the RGB is ~10^2−10^3 L_☉, which lowers the Groenewegen value for M by up to a factor 5. If the winds are as fast as sometimes seen in chromospheric lines of warmer RGB stars (Mauas et al. 2006; McDonald & van Loon 2007) then M could be higher. We thus settle on a conservative estimate of M = 10^{-8} M_☉ yr^{-1}. The mass-loss rate may still be higher if the dust-to-gas ratio is lower than assumed—in spite of the high abundance of condensable material. However, our estimate compares favorably with the empirical relationships of Reimers (1977) and Schröder & Cuntz (2005) which yield M ∝ 10^{-4} and a few 10^{-9} M_☉ yr^{-1}, respectively, for a typical RGB star of 1 M_☉, 4000 K, and 500 L_☉. This suggests that the basic assumptions we made are not unreasonable.

If such mass loss is sustained over 19% (the observed fraction of dusty stars) of the time it takes to evolve along this part of the RGB, t = 8 × 10^7 yr (Marigo et al. 2008), then they will lose ΔM = 0.2 M_☉—insufficient to avoid the helium flash. These stars were born with a mass M_{initial} = 1.1 M_☉, and would need to shed ΔM_{implanted} = 0.7 M_☉ to produce white dwarfs of the masses measured by Kalirai et al. (2007). Both Kalirai et al. (2007) and Hansen (2005) point out that not all RGB stars may avoid the helium flash. Given the above estimates of M, fraction of dusty stars, and RGB lifetime, the Spitzer data suggest that no more than M/ΔM_{implanted} × 19% or ≤2% of RGB stars in NGC 6791 can sustain the required heavy mass loss.

There is a possibility that we have missed a star at the very tip of the RGB losing mass at a high rate, but only briefly before it leaves the RGB. Indeed, dust-accompanied mass loss, at rates as high as 10^{-8} M_☉ yr^{-1}, is seen to happen predominantly near the tip of the RGB (van Loon et al. 2006; Origlia et al. 2007; McDonald & van Loon 2007) then could be higher. We thus settle on a conservative estimate of 10^{-8} M_☉ yr^{-1}.

5. THE RGB LUMINOSITY FUNCTION

To explain white dwarf masses 0.1 M_☉ lower than the core mass at the tip of the RGB, the luminosity function must be depleted over 0.6 dex in log L (Table 2 in Castellani & Castellani 1993), corresponding to 1.5 mag. We demonstrate below that such depletion in NGC 6791 is not corroborated by the measurements.

We constructed cumulative luminosity functions (LFs), in both the Spitzer IRAC bands and the V band (Fig. 6). The IR and V-band LFs were aligned such that the very obvious bump due to the red clump coincides—this required a shift toward brighter values of the V-band LF by 3 mag. This difference, and the much steeper bright end to the V-band LF compared to the IR LFs, are due mainly to the bolometric corrections to the V band (BC_v) of the increasingly cooler RGB stars as they approach the RGB tip [a small contribution is due to the extinction, E(B − V) ≈ 0.14; Kalirai et al. 2007].

The observed LFs compare favorably with model LFs from the Padua group (Marigo et al. 2008), displayed in the bottom panel of Figure 6. The models, displayed for a distance modulus of 13.0 mag, show the same shape and location of the red clump and main sequence (the rise in the V-band LF at the faint end of the scale). The models, which do not include mass loss along the RGB, reproduce the observed difference at the bright end between the IR and V-band LFs rather well. The most metal-rich Padua model is with Z = 0.03 not quite as metal-rich as...
NGC 6791 (Z = 0.05), and if compared to the Z = 0.02 Padua model it is evident that a Z = 0.05 model LF would be truncated at even fainter magnitudes, in close agreement with the observed LF. This is corroborated by the good fit to the optical color-magnitude diagram of a Z = 0.06 isochrone using the Reimers (1977) mass-loss prescription (Claret 2007). Kalirai et al. (2007) find that the V-band LF of NGC 6791 is depleted with respect to the (sub)solar metallicity clusters Berkeley 17 and M67, over the top magnitude of the RGB. They do not, however, consider that BCV also differs by >1 mag (Marigo et al. 2008), nor the effects from contamination by field stars.

With regard to the IR LF, which more accurately measures the bolometric output of these stars, the difference with the models can be entirely explained by stochastic effects. The NGC 6791 cluster is not populous enough to harbor many stars near the RGB tip; while there are few tip RGB stars present now, it is conceivable that one or two more may have been present several million years ago or will be present several million years from now. It can also not be excluded that a tip RGB star was missed, for instance, because it had fallen outside the Spitzer coverage, or because of an inaccuracy in the proper-motion measurement, or for other observational reasons. To demonstrate the feebleness of any indication of a prematurely truncated RGB, the 8 μm LF is shown again after adding a mere two stars at the tip of the RGB. This brings the observed LF in excellent agreement with the theoretical prediction. Indeed, the relative numbers of post-helium-flash red clump stars compared to those at similar luminosities on the RGB are well reproduced (Fig. 6), suggesting that the vast majority of RGB stars do go on to undergo the helium flash.

6. CONCLUSIONS

We conclude that there is good agreement between the observed and expected optical and infrared luminosity functions along the RGB in NGC 6791, and that there is little circumstellar dust observed around RGB stars in that old, metal-rich, massive open cluster. Hence there is no direct evidence supporting the suggestion that metal-rich stars avoid the helium flash at the tip of the RGB and become undermassive helium-core white dwarfs as a result of particularly strong stellar winds.

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Fig. 6.—Spitzer IRAC and optical V-band (Stetson et al. 2003) luminosity functions in NGC 6791. The 8 μm luminosity function is also plotted after adding just two more stars near the tip of the RGB. A comparison with 8 Gyr Padua models (Marigo et al. 2008) shows good agreement, especially considering that NGC 6791 is more metal-rich. Stochastics introduced by sampling the small number of stars on the upper RGB can fully explain the discrepancy between the data and models.

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