DUST IS FORMING ALONG THE RED GIANT BRANCH OF 47 Tuc

Livia Origlia1, Robert T. Rood2, Sara Fabbri3, Francesco R. Ferraro3, Flavio Fusi Pecci1, R. Michael Rich4, and Emanuele D'Alessandro3

1 INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy; livia.origlia@oabo.inaf.it, flavio.fusipecci@oabo.inaf.it
2 Astronomy Department, University of Virginia, Charlottesville, VA 22903, USA; rtr@virginia.edu
3 Dip. di Astronomia, Università degli Studi di Bologna, Via Ranzani 1, I-40127 Bologna, Italy; sara.fabbri@studio.unibo.it, francesco.ferraro3@unibo.it, emanuele.dalessandr2@unibo.it
4 Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095-1547, USA; rmr@astro.ucla.edu

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ABSTRACT

We present additional evidence that dust is really forming along the red giant branch (RGB) of 47 Tuc at luminosities ranging from above the horizontal branch to the RGB tip. The presence of dust had been inferred from an infrared excess in the \((K - 8)\) color, with \(K\) measured from high spatial resolution ground-based near-IR photometry and \("8\) referring to Spitzer-Infrared Array Camera (IRAC) 8 \(\mu m\) photometry. We show how \((K - 8)\) is a far more sensitive diagnostic for detecting tiny circumstellar envelopes around warm giants than colors using only the Spitzer-IRAC bands, for example, the \((3.6 - 8)\) color used by Boyer et al. In addition, we also show high-resolution Hubble Space Telescope Advanced Camera for Surveys \(I\)-band images of the giant stars that have \((K - 8)\) color excess. These images clearly demonstrate that the Boyer et al. statement that our detections of color excess associated with stars below the RGB tip arise from blends and artifacts is simply not valid.

Key words: infrared: stars – stars: individual (Population II) – stars: mass-loss – techniques: photometric

1. INTRODUCTION

In Origlia et al. (2007), we presented estimated mass-loss rates for the first ascent red giant branch (RGB) stars in the globular cluster 47 Tuc. These were based on near- and mid-infrared photometry obtained from a Spitzer-Infrared Array Camera (IRAC; 3.6, 4.5, 5.6, and 8 \(\mu m\)) survey and ground-based high-resolution \(JHK\) observations. We found about 100 giants with \((K - 8)\) color excess that we attributed to the presence of dusty circumstellar envelopes. These candidate dusty stars were mainly found in the inner \(2′\) (in radius) and had luminosities ranging from above the level of the horizontal branch (HB) to the RGB tip. For a given luminosity only a fraction of stars exhibited this color excess, and this fraction increases toward the tip of the RGB. From the color excess, we derived a mass-loss rate and found a shallower dependence on luminosity than that expected from the Reimers (1975a, 1975b) formula. After correcting the observed frequency of dusty envelopes for incompleteness, we derived an average duty cycle which could be used along with the observed mass-loss rates and evolutionary times to compute the total amount of mass lost on the RGB.

Recently, Boyer et al. (2010), using the \((3.6 - 8)\) Spitzer-IRAC color as their main diagnostic tool, found evidence for a dust excess only in asymptotic giant branch (AGB) stars and possibly a few giants near the RGB tip. On the basis of this finding, they concluded (see also Boyer et al. 2008, 2009) that our candidate dusty giants below \(M_{bol} \approx -2.5\) were spurious, mainly blends and/or artifacts. We emphasize that (1) this conclusion was not based on a direct star-to-star check and (2) their analysis employed a different diagnostic, and it was not optimized to cover the innermost region of the cluster sampled by our work. The \(AKARI\) analysis of 47 Tuc presented by Ita et al. (2007) also showed dust excess only near the tip, but it did not have the spatial resolution to properly investigate the stellar population in central regions of globular clusters. We ourselves using ISOCAM found circumstellar dust excess only near the RGB tip (Origlia et al. 2002), again because of the lower spatial resolution of ISOCAM compared to IRAC.

In this paper, we respond to the Boyer et al. (2010) criticism. We demonstrate the importance of an optimum sampling of the innermost region of the cluster where most of the red giants, along with the rest of the stellar population, are found. We show that \((K - 8)\) is a much better diagnostic of dusty giants than \((3.6 - 8)\). Finally, using a high-resolution Hubble Space Telescope Advanced Camera for Surveys \(I\)-band image, we clearly demonstrate that our detected \((K - 8)\) color excess in giant stars below the RGB tip is not an effect of blending and/or an artifact.

2. PHOTOMETRIC SAMPLES

Many of the contentions of Boyer et al. (2010) arise from their misunderstanding of the “shallow” and “deep” samples of Origlia et al. (2007). It is clearly stated in Section 2 and in the caption of Figure 2 of Origlia et al. (2007) that shallow and deep do not refer to the short and long Spitzer exposures. Both the shallow and deep samples include photometry from short (0.6 s) and long (12 s) exposures. We use the shortest exposures to measure the brightest stars near the RGB tip, which are saturated in the long exposures. The long exposures are averaged to study the fainter stars. The shallow sample refers to a \(8′ \times 8′\) rectangular area photometrically cut at \(K = 11\) (or \(M_{bol} \sim 0\)), since at fainter magnitudes crowding severely affects the photometric accuracy in the central region. The deep sample down to \(K \approx 14\) excludes the central \(2′\) in radius.

The Rood-shallow and Rood-deep samples of Boyer et al. (2010) have no correspondence with the shallow and deep samples of Origlia et al. (2007), either in terms of the sampled region or in terms of the total exposure time. The Boyer et al. (2010) Rood-deep sample includes the very center of the cluster, so they find more scatter. They do discuss completeness of

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their samples, but in detecting color excesses, scatter is more important than completeness. We feel that their sampling of the central part of the cluster is adequate to detect only the brightest dusty stars. They do discuss the region with $R > 3'$ separately but that does not correspond to our deep sample at $R > 2'$. Their deep samples in the $3' < R < 10'$ range have small overlap with the $5' \times 8'$ field of view sampled in Origlia et al. (2007). We have examined our subsample at $R > 3'$ and find that only one dusty AGB star has been detected, fully consistent with the Boyer et al. (2010) finding in this outer region.

### 3. DIAGNOSTIC PLANES

Boyer et al. (2010) claim that the $M_{bol}$, $(3.6 - 8)$ diagnostic plane that they use is as effective in detecting dusty giants as the $M_{bol}$, $(K - 8)$ plane used by Origlia et al. (2007). Other than stating that dust emission at 3.6 $\mu$m is negligible, they do not provide any direct test of their supposition.

Figures 1 and 2 show $M_{bol}$, $(K - 8)$ and $M_{bol}$, $(3.6 - 8)$ color–magnitude diagrams (CMDs) of the shallow and deep samples from Origlia et al. (2007) photometry. Triangles mark those stars with a $3\sigma$ excess in the $(K - 8)$ color. Circled triangles show those that also have a $3\sigma$ excess in the $(3.6 - 8)$ color.

Figure 3 shows the $(K - 8)$, $(3.6 - 8)$ color–color diagram. Triangles mark those stars showing a $3\sigma$ excess in the $(K - 8)$ color. Filled triangles show those that also have a $3\sigma$ excess in the $(3.6 - 8)$ color.

The figures all show that the $(K - 8)$ color is far more effective than the $(3.6 - 8)$ color in disentangling relatively warm ($T_{eff} > 4000$ K) photospheres from optically thin, warm ($T_{dust} > 500$ K) dusty envelopes. Most of the candidate dusty stars identified by Origlia et al. (2007) have $(3.6 - 8)$ colors in the 0.1–0.3 mag range, barely (if at all) exceeding the $3\sigma$ photometric uncertainty which ranges from 0.15 at $M_{bol} < -2$ to 0.25 at $M_{bol} \approx 0$. The $(K - 8)$ color always exceeds 0.2 mag and spans a larger range. We recall that, according to the simulations with the DUSTY code, these $(K - 8)$ and $(3.6 - 8)$ colors are those of a dust that is optically thin ($\tau_8$ is in the $10^{-4}$ to $10^{-2}$ range) and made of silicates, i.e., a chemical composition typical of O-rich environments as the circumstellar envelopes of low-mass giants. Such a dust has IRAC–Spitzer color temperatures in the 400–800 K range.

In relatively warm and low-luminosity giants, like low-mass RGB stars, the fractional contribution of the warm dust emission to the 3.6 $\mu$m is not negligible and not much smaller than the dust contribution at 8 $\mu$m. Indeed, in the measured giants of 47 Tuc we estimate that the average dust contributions are 20% at 3.6 $\mu$m and 30% at 8 $\mu$m. The fractional contribution of dust emission at 3.6 $\mu$m is negligible only in much cooler and more luminous giant stars and/or in the case of envelopes with a large amount of dust.

Hence, when using the $(3.6 - 8)$ color to select candidate dusty RGB stars in globular clusters, as done by Boyer et al. (2010), one is clearly biased toward the coolest (hence the most luminous) ones and with relatively large amount of circumstellar dust.

### 4. BLENDS AND ARTIFACTS

Since the IRAC–Spitzer pixel is relatively large, it is possible that more than one star actually falls in it. Hence blending is an obvious worry near cluster centers, although only a rather special kind can mimic a dusty star. If more than one star blends together in the 8 $\mu$m point-spread function (PSF), and the blending object
Figure 2. $M_{bol}$, $(K - 8)$ (left) and $M_{bol}$, $(3.6 - 8)$ (right) CMDs of the 47 Tuc deep sample of Origlia et al. (2007), i.e., within a rectangular region of 5' × 8' around the cluster center, but excluding the central region, $r < 2'$. Triangles are stars with a $3 \sigma$ $(K - 8)$ color excess. Circled triangles are stars that also have a $3 \sigma$ $(3.6 - 8)$ color excess.

Figure 3. $(K - 8)$, $(3.6 - 8)$ color–color diagram of 47 Tuc within a rectangular region of 5' × 8' around the cluster center. Triangles are stars with a $3 \sigma$ $(K - 8)$ color excess. Filled triangles are stars that also have a $3 \sigma$ $(3.6 - 8)$ color excess.

This does not fall in the $K$ or 3.6 $\mu$m PSF, a bogus IR excess can result. However, we emphasize that to produce an appreciable excess the blending star(s) must be comparable in brightness (say within a factor of 10) to the first star. More precisely, the $3 \sigma$ color excess on the upper RGB is $(K - 8) > 0.15$. The blending stars would require 8 $\mu$m luminosities within a factor of roughly 6 (2 mag) to produce a significant excess. On the lower RGB the $3 \sigma$ color excess is $(K - 8) > 0.15$, and the luminosities would have to be within a factor of 4 (1.3 mag). Given that the RGB of a globular cluster is practically vertical in the $K_{s}$, $(K - 8)$ CMD (i.e., the same $K - 8$ color for normal giants), differences in luminosity within factors of 4–6 are also required in the $K$ band. The corresponding $I$-band luminosities should vary only by factors of 2.5–4 (i.e., stars cannot differ by more than 1–1.5 mag in the lower and upper RGB, respectively).

In Boyer et al. (2010) and earlier papers (Boyer et al. 2008, 2009) on different clusters, the authors have made much of the possibility of blending and argued that the bulk of the dusty stars in Origlia et al. (2007) are blends. We stress that their statement is not based on a direct inspection of the stars in our sample, but simply on the appearance of their CMDs in a different photometric plane, in different sampled regions, or even in different clusters. To estimate the possible magnitude of the blending problem, Boyer et al. (2010) employ a deconvolution technique in which the 3.6 $\mu$m images are analyzed using the 8 $\mu$m PSF. While this technique might give some estimate of the magnitude of blending problems, it is definitely less effective than a direct inspection of high spatial resolution optical/near-IR images as done in Origlia et al. (2007).

In order to definitely solve the issue of blending, we have obtained an HST-ACS $I$-band image of 47 Tuc from the archive. Figure 4 shows 78 of 93 candidate dusty giants. For the majority (72 out of 78) of stars (the top panel in Figure 4), only the target and a few (if any) significantly fainter stars are present within the IRAC-Spitzer PSF area. These stars, which are typically at
least 2–3 mag fainter, cannot be responsible for the observed color excess. The only possible exceptions are ID-351, 373, and 489, where the neighboring stars are ∼1 mag fainter. ID-351 is also a blend in the near-IR K images, so at least one of the two components (probably the brighter one) is likely responsible for the observed color excess. ID-373 and 489 both have a color excess exceeding ∼0.6 mag, which is too large to be accounted for by a blending star ∼1 mag fainter.

Among the remaining six candidate stars (the bottom panel in Figure 4) with color excess, ID-76 and ID-103 are only marginally blended, while the two stars blending ID-240 are not bright enough to produce a detectable excess. ID-445, 454, and 479 are a blend of two stars with similar luminosity both in the near-IR and Spitzer PSFs. In this case, we cannot precisely identify the star(s) responsible for the color excess but at least one has it.

The other 15 candidate dusty giants not imaged by ACS lie in the outer region of the field of view covered by our Spitzer and near-IR surveys, where crowding is less of a problem. Indeed, 12 are definitely free from blends by stars bright enough to produce a detectable excess, while 3 (2 of which are AGB stars) are only partially blended.

Hence, just as we described in Section 2 of Origlia et al. (2007), a suitable cross-correlation with high spatial resolution optical and/or near-IR stellar catalogs allows for (1) a proper identification of the stellar counterpart, (2) the correct determination of the star photospheric parameters, and (3) a direct way to check for and remove possible blends, artifacts, background galaxies, etc. It is also worth noting that Origlia et al. (2007) used ROMAFOT (Buonanno et al. 1983), a software package optimized to perform PSF fitting photometry of crowded fields even in a regime of under-sampling, as with Spitzer-IRAC at the

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**Figure 4.** ACS I-band images of 78 candidate dusty stars in 47 Tuc. The field of view of each image is 5′ × 5′ and the circles (∼1″ in radius) mark the 8 μm PSF area of IRAC.
shortest wavelengths. ROMAFOT allows one to directly inspect
the fit of faint and/or problematic sources to double check possible
residual blending, artifacts, background galaxies, etc., and
to remove them. Objects identified as blends have been rejected
as dusty giants. Blending turned out to be a rare event ($P < a$
few percent in the lower RGB and $P \simeq 0$ in the upper RGB) in
mimicking color excess, as expected.

Another indication that blending is not a problem is the
absence of any correlation between the occurrence of blending
and luminosity in the sampled RGB portion. Figures 1 and 2
also show that most of the candidate dusty giants are confined
within the central 2′. This might be taken as an indication of
blending, but it turns out that it is just what is expected.
If the dusty stars are real they should be distributed like the
cluster light. False dusty stars arising from crowding should be
preferentially found in regions of high density. Using a King
model of the cluster, we find that of the total bolometric light
sampled in the central 2′ (in radius) about 64% is contained in
the central 1′ and 36% in the annulus between 1′ and 2′. The
corresponding fractional number of dusty giants in the same
regions are 67% ± 11% and 33% ± 7%. Very similar results
within the errors (i.e., 61% ± 5% and 39% ± 4%, respectively)
are obtained by counting non-dusty stars. The observed numbers
are completely consistent with model expectations and this
should be the case if crowding is not a problem.

Boyer et al. (2010), relying on Spitzer data alone, may be
bothered by instrumental artifacts. We have no such problem
since our high spatial resolution optical and near-IR data have
no (or at least different) artifacts.

In summary, the Boyer et al. (2010) conclusion that Origlia
et al. (2007) candidate dusty RGB stars below the tip are false
detections is not justified.

5. DISCUSSION AND CONCLUSIONS

The ($K - 8$) color excess detected by Origlia et al. (2007)
in a fraction of RGB stars down to $M_{bol} \sim 0$ within the central
2′ of 47 Tuc is real. It is not an artifact, since blends and other
possible spurious effects have been properly accounted for by
cross-correlating the Spitzer sources with high spatial resolution
optical and near-IR catalogs of stellar counterparts.

The fact that Boyer et al. (2010) did not find as many dusty
stars in the central 2′ is mainly due to the use of a different
diagnostic, namely the (3.6 − 8) color, which is only effective
for detecting dust excess in cooler (hence more luminous)
giants. Further, their photometric analysis is not optimized in
the central, densest region. Boyer et al. (2010) find only few
dusty giants in the outer regions, fully consistent with Origlia
et al. (2007) and the additional CMDs shown in Figure 2.

As discussed in Section 4 of Origlia et al. (2007), mass-loss
rates and duty cycles decrease with decreasing stellar luminosity.
For a given luminosity, the estimated rates are higher (between
a factor of 2 near the tip up to 2 orders of magnitude down to
$M_{bol} \sim 0$ than those predicted by the Reimers law, as also noted
by Boyer et al. 2010). The shallower slope we found has also
been suggested by Meszaros et al. (2009), from chromospheric
line wind diagnostics of giants in metal-poor clusters. The
Reimers result was obtained from Population I objects, and
one might anticipate some differences. Our higher mass-loss
rate is not a major problem, given that both the Reimers law
and our results contain free parameters: (1) the Reimers efficiency
$\eta$ and (2) the gas-to-dust ratio and expansion velocity. In either
case, the free parameters must be set by indirect observational
constraints on the total mass lost during the RGB evolution like
the HB morphology.

The total mass loss occurs predominantly in the upper ~2 mag
near the RGB tip. The contribution of the low-luminosity giants
($M_{bol} > -1$) is small (< 20%) to negligible, and within the
estimated uncertainty. The importance of our observation of
mass loss in less luminous stars is not its impact on total mass
lost, but rather the clue it gives us to the physics of mass loss.
Likewise, the episodic nature of mass loss in non-variable stars
tells us something. In both cases, it seems quite clear that the
underlying driver of the mass loss is not radiation pressure on
dust. Another important outcome of our larger project will be an
investigation of the differential mass loss among clusters with
different metallicities and HB morphologies. This has been the
goal of our Spitzer survey and the complementary ground-based
observations, and the results will appear in forthcoming papers.

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