CONSTRAINING NEUTRINO COOLING USING THE HOT WHITE DWARF LUMINOSITY FUNCTION IN THE GLOBULAR CLUSTER 47 TUCANAE

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ABSTRACT

We present Hubble Space Telescope observations of the upper part (T_{eff} > 10^4 K) of the white dwarf cooling sequence in the globular cluster 47 Tucanae and measure a luminosity function of hot white dwarfs. Comparison with previous determinations from large-scale field surveys indicates that the previously determined plateau at high effective temperatures is likely a selection effect, as no such feature is seen in this sample. Comparison with theoretical models suggests that the current estimates of white dwarf neutrino emission (primarily by the plasmon channel) are accurate, and variations are restricted to no more than a factor of two globally, at 95% confidence. We use these constraints to place limits on various proposed exotic emission mechanisms, including a nonzero neutrino magnetic moment, formation of axions, and emission of Kaluza–Klein modes into extra dimensions.

Key words: astroparticle physics – dense matter – elementary particles – neutrinos – stars: luminosity function, mass function – white dwarfs

1. INTRODUCTION

Despite its modest beginnings in a sheepish proposal by Pauli in his famous letter of 1930,5 the neutrino has emerged as an object of great interest to the contemporary particle physics community. The interpretation of solar and atmospheric neutrino data (Davis et al. 1968; Fukuda et al. 1998) in terms of neutrino oscillations requires that neutrinos have finite mass and exhibit flavor mixing, which is one of the few pieces of evidence that currently points to the existence of physical phenomena beyond the standard model of particle physics. However, the small interaction cross section of neutrinos means that they are quite difficult to produce and to study in terrestrial experiments. On the other hand, certain classes of stars produce neutrinos in copious quantities, and neutrino cooling plays an important role in certain aspects of stellar evolution.

Indeed, when central densities ρ > 10^4 g cm^{-3} and central temperatures are ~10^8 K, the stellar luminosity in neutrinos can exceed that in photons (Fowler & Hoyle 1964; Vila 1966; Lamb & Van Horn 1975). Such conditions are realized during the core evolution of intermediate-mass stars, and neutrino cooling regulates the rate of evolution of stars as they transition from the asymptotic giant branch to the top of the white dwarf cooling track. Models for masses ~0.53 M_⊙, an appropriate mass for those white dwarfs forming in old globular clusters today, show that for the first ~5 × 10^6 yr of the white dwarf’s existence, the rate of cooling is dominated by neutrino emission. Thus, if we can amass a large enough sample of white dwarfs with ages <10 Myr, the study of the resulting hot white dwarf luminosity function (LF) can provide a direct test of our understanding of neutrino emission in astrophysical settings.

Such studies became a possibility with the construction of an LF for hot white dwarfs in the solar neighborhood from the Palomar-Green survey (Fleming et al. 1986). The resulting comparison with models for the population evolution of young white dwarfs enabled tests of our understanding of neutrino emission, including constraints on the possibility of extra cooling from hot cores due to the existence of processes beyond the standard model, such as axion emission or the existence of a neutrino magnetic moment (Wang 1992; Blinnikov & Dunina-Barkovskaya 1994). However, the short evolutionary timescales and relative rarity of hot white dwarfs meant that these constraints were not improved until the advent of the modern era of large-scale sky surveys, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) or SuperCosmos Sky Survey (Hambly et al. 2001). This has led to a resurgence of interest in this question, with improved constraints on the hot white dwarf LF presented by De Gennaro et al. (2008), Krzesinski et al. (2009), and Rowell & Hambly (2011) and resulting theoretical analyses (Isern et al. 2008; Miller Bertolami 2014).

However, the construction of an LF from an all-sky survey must confront a variety of selection effects, including a nonuniform selection for spectroscopic follow-up and biases in the assignment of absolute magnitudes due to distance uncertainties (see Krzesinski et al. 2009 for a discussion). As a result, we describe here the construction of a hot white dwarf LF from an alternative source, namely, the globular cluster 47 Tucanae. This project is a follow-up to a previous deep observation to constrain the LF of cool white dwarfs (Goldsbury et al. 2012; Hansen et al. 2013) but with a wider field coverage (albeit to shallower depth) and UV exposures, in order to increase the number of bright white dwarfs detected. This program has an advantage over all-sky surveys in that all the white dwarfs lie at the same distance and are selected in a uniform manner, albeit with its own selection effects, to be discussed below. As such, our resulting LF provides a constraint on hot white dwarf physics that is completely independent of that derived from the stars in the solar neighborhood.

5 Reprinted, in translation, in Brown (1978).
We describe below (Section 2) two sets of observations taken with the Hubble Space Telescope (HST) in 47 Tucanae. In Section 3 we compare these to a set of white dwarf atmospheric models and describe the resulting construction of the hot white dwarf bolometric LF. We also describe the construction of a set of theoretical cooling models (Section 4) used to explore the possible ranges of physical inputs for comparison to the observations, including explorations of the neutrino physics, possible nonstandard contributions to the luminosity, and potential sources of confusion, such as uncertainties in the thickness of the hydrogen layer on the surface of white dwarfs. Finally, in Section 5 we compare the models and the data to place constraints on the various parameters discussed.

2. OBSERVATIONAL DESIGN AND DATA ANALYSIS

The observational design of this program (GO-12971; PI H. Richer) involves parallel imaging observations with HST’s WFC3 and Advanced Camera for Surveys (ACS) cameras. The data were collected from 2012 November 14 to 2013 September 20. The 10 orbits were split into 10 visits, each one with an orientation offset to ensure a 360° mapping of the cluster central region when all data are combined together. In this arrangement, the center of 47 Tuc was placed near the corner of all WFC3 observations, so the contiguous region from the mosaic extends approximately one WFC3 diagonal field in radial extent. The parallel ACS pointings approximately abut the WFC3 fields and therefore complete an annulus around the cluster center. Taken together, this arrangement provides high-resolution HST imaging covering the inner 8′5 of 47 Tuc.

The data analysis was performed using the prescription and procedures described in Kalirai et al. (2012). Within each visit, the observations contain two WFC3 exposures in F225W (380 s and 700 s) and F336W (485 s and 720 s) and two ACS exposures in F435W (290 s and 690 s) and F555W (360 s and 660 s). For the WFC3 observations, we retrieved the _raw and _flt frames and corrected the data for charge transfer efficiency (CTE) losses using the WFC3 pixel-based empirical CTE correction software (http://www.stsci.edu/hst/wfc3/tools/cte_tools). For the ACS data, we retrieved the _flc (i.e., CTE-corrected) frames directly from the MAST archive. For each filter on the WFC3 data, we executed a first pass of MultiDrizzle (Fruchter & Hook 2002) to generate geometric-distortion-corrected images. We then performed astrometry on the stars in these images (using the DAOPHOTII software; Stetson 1987, 1994) and calculated transformations that mapped all images on the 10 visits to the same frame of reference. These offsets and rotations were then supplied to MultiDrizzle in a second pass as a “shift” file, and a stacked (i.e., drizzled) image was produced in each filter for the entire 10-visit mosaic. Given the small overlap of the 10 pairs of images, we did not rescale the images or adjust the “pixfrac” parameter in MultiDrizzle. As the ACS data contain negligible overlap among the 10 fields, each of the fields was treated independently to create 10 drizzled images from the pairs.

The single drizzled WFC3 image in each filter and the 10 drizzled ACS images in each filter were subjected to point-spread function (PSF) fitted photometry and morphology using DAOPHOT II. As described in Kalirai et al. (2012), our procedure involved finding all sources that are at least 2.5σ above the local sky, selecting candidate PSF stars based on their brightness and isolation, generating a spatially variable PSF from these stars, and applying the PSF to all sources in the image using ALLSTAR. The resulting photometry from each filter was zero pointed to the VegaMAG system, and the photometry from the two filters on each camera was matched into a single catalog.

2.1. The Core Field

The color–magnitude diagram (CMD) of all stars in the WFC3/UVIS drizzled image is shown in Figure 1 and displays a clear white dwarf cooling sequence extending to F225W ∼ 25. At these short wavelengths, the main sequence of the background SMC is less prominent than at other wavelengths (e.g., Hansen et al. 2013; Kalirai et al. 2013; and Section 2.2). The dashed curve shown in Figure 1 is used to identify the white dwarf population for the purposes of constructing an LF.

The approximate transition temperature between neutrino-dominated cooling and photon-dominated cooling is ~25,000 K. A white dwarf with this temperature and log g = 8, at a distance of μ0 = 13.3 and a reddening of E(B − V) = 0.04 (nominal 47 Tuc parameters), will have F336W ∼ 22.1. Our LF contains 216 white dwarfs brighter than this threshold. Although the exact value of this transition will vary depending on the distance, extinction, and white dwarf parameters, it is clear that our data contain a substantial population of white dwarfs whose principal cooling mode is via the emission of neutrinos.

To assess the photometric and astrometric error distribution of the final photometry in our images, as well as the completeness of the data reductions, we performed artificial star tests. The artificial stars are modeled from the stellar PSF and scaled to reproduce the complete luminosity range of real stars in the drizzled images of each filter. The input stars were placed along each of the white dwarf and main sequence of 47 Tuc, and the input positions were set such that no two artificial stars overlapped each other on the image. As the mosaicking of our data set results in deeper observations near the center of the cluster (i.e., exposures from all visits overlap in the core), we placed the artificial star tests over the complete radial range of our fields. The procedure to do this involved placing stars with the same intensity in radial grids. A total of 25 million artificial stars were used. The images with artificial stars were subjected to the photometric routines that were applied to the actual drizzled images, using identical criteria. The stars were recovered blindly and automatically cross-matched to the input star lists containing actual positions and fluxes.

2.2. The Outer Fields

Figure 2 shows the CMD from the ACS parallel fields. The presence of the SMC main sequence is much more prominent in these redder filters, and the photometric scatter is larger because the exposure time per object is ~10% that of the stars in the core data. As a result, the definition of the white dwarf cooling sequence becomes more ambiguous for F555W > 24.5, as the white dwarfs and SMC main sequence start to overlap. Nevertheless, we can still see a well-sampled LF for bright white dwarfs.

The increased field coverage of the ACS data partially compensates for the lower stellar density relative to the core.
The stellar density at \( \sim 3'–4' \) (the distance of the parallel fields from the cluster center and slightly larger than the cluster half-mass radius; Trager et al. 1993) is more than an order of magnitude lower than that averaged over the WFC3 field (which encompasses \( \sim 2'7 \)), so that the increase in areal coverage by a factor of 10 results in the detection of 89 white dwarfs with \( F555w < 23.5 \) (the magnitude for white dwarfs with \( T_{\text{eff}} = 25,000 \text{ K} \) and the same distance and extinction as used for the WFC3 estimate). We follow the same artificial star procedures as in Section 2.1 to estimate completeness and photometric scatter. The radial dependence is much less in the ACS fields, because they lie at several core radii from the cluster, where the density gradient is much smaller across the field.

3. FITTING ATMOSPHERIC MODELS TO THE DATA

Our two data sets represent two observations of the same class of stars in multiple bandpasses and spatial locations in the cluster. The underlying atmospheric models should be the same in both bandpasses, and so we can hope to constrain the distance and extinction to the cluster based on fitting the position of the cooling sequence in both CMDs simultaneously.

In Section 5 we will fit the data to models that include cooling histories, but we can compare the model and observed colors independently of the cooling history. This is because the position of the cooling sequence in the CMD depends on the model atmosphere, while the distribution of stars along the cooling sequence is determined by the rate of cooling. To constrain the former alone, we calculate the mean white dwarf color as a function of magnitude (in 0.25 mag bins) in both the core and swathe fields, and we fit an atmosphere model for a range of assumed white dwarf mass, extinction, and distance, using the artificial star tests to estimate photometric scatter as a function of magnitude. We also considered various values of the surface hydrogen layer mass, which can influence the radius of hot white dwarfs. Figures 3 and 4 show the resulting best fits in both cases.

For the ACS data, the best-fit distance is \( \mu_0 = 13.21 \pm 0.16 \), for an extinction \( E(B-V) = 0.04 \pm 0.02 \). The best fits are obtained for masses \( \sim 0.51–0.53 M_\odot \) and hydrogen envelope mass fractions \( q_{\text{H}} = 10^{-4} \). The error bar on this determination is larger than our previous measurements in Woodley et al. (2012) and Hansen et al. (2013) because the more limited magnitude range of the data allows for more covariance between distance, extinction, and mass than in those analyses. The value here is slightly lower than in those cases (13.36 \( \pm 0.08 \) and 13.32 \( \pm 0.09 \), respectively) but still consistent within the error bars. The constraint will be improved in Section 5 when we use the full information in the cooling models.

The best-fit distance for the core data is \( 13.08 \pm 0.08 \), again favoring white dwarf masses \( \sim 0.51–0.53 M_\odot \), but now the best fits are obtained for low extinctions and large hydrogen layer masses. Indeed, inspection of the comparison between models and data in Figure 4 suggests that the atmosphere models are not a good representation of the data in these
passbands, as they are too blue at magnitudes $F336W > 23$. Furthermore, the fits favor low extinction because the color asymptotes to a value at bright magnitudes that is a poor match to the observed values, which drags the fitted extinction down and increases the mismatch at the faint end. The modeling of the core white dwarf sequence is further complicated by the effects of spatially varying completeness and the possibility of radial diffusion of stars relative to dynamical relaxation. However, neither of these effects can explain the discrepancy here, because the best-fit color is determined at each magnitude independently and does not depend on the relative numbers as a function of magnitude.

3.0.1. Causes of the Discrepancy

A variety of tests were performed to identify the source of the discrepancy between the data and the available atmosphere models at the faint end of the UV white dwarf cooling sequence. These included re-drizzling smaller sections of the image mosaic that excluded the dense core of 47 Tuc and performing PSF photometry on these regions, adjusting the sky subtraction algorithm to correctly subtract the diffuse light between different frames, adjusting the annulus over which the sky is measured in the photometry to test for red leaks that were not being accounted for, and exploring a range of apertures in a separate trial of aperture photometry analysis of the non-crowded regions. We also performed a completely independent analysis of the data without the drizzling algorithm and with a different PSF-fitting photometric algorithm (J. Anderson 2015, private communication). All of these tests resulted in colors for the faint white dwarfs consistent with our baseline reduction.

Subsets of our core field mosaic overlap observations in other WFC3 UV filters, including $F275W$ (GO-12311; PI. G. Piotto) and $F390W$ (GO-11664; PI. T. Brown). We retrieved all of these data from MAST and subjected them to the same drizzling and PSF-fitting operations as our baseline data set, and we matched the positions of sources across all four filters. While these data do not have the same depth and spatial coverage as our new observations, they hint that the color offset with respect to the models may also appear in other color combinations that span a wavelength of $\sim 300$ nm (e.g., a possible offset is also seen in an $F275W$ versus $F390W$ comparison).

The source of this mismatch remains a mystery and could be the consequence of one or more independent reasons. For example, the images in the redder filters like $F336W$ and $F390W$ have a very high level of crowding as we approach the cluster center, and therefore the completeness is $<75\%$ even at 2 core radii. Hence, if there is a systematic issue with the photometry that is not being accounted for by the artificial star tests, then incompleteness could be the cause. Alternatively, it is possible that the observed colors are correct and rather the current generation of white dwarf atmosphere models lack an important source of opacity at UV wavelengths.
3.1. The Bolometric Luminosity Function

The data presented here represent a new opportunity to construct an LF for hot white dwarfs. This is particularly difficult in the field because the short cooling times imply that hot white dwarfs are relatively rare, requiring large-scale surveys to characterize them. Observations in a globular cluster can isolate a well-defined sample and better illuminate features of the LF, at the price of foregoing some of the more detailed atmospheric characterization possible from spectra of the closer field stars. In Section 5 we will provide a detailed model fit to the data, but for the purposes of comparison to prior studies, it is also worthwhile to present the data in the same form as in other studies.

The construction of an absolute bolometric magnitude requires the adoption of a cluster distance and reddening. Fortunately, the sparseness of the data in wide-field surveys means that we can compare results in relatively large (1 mag) bins, which renders the uncertainties in the discussion above (of the order of 0.1 mag) irrelevant. We will adopt $m_0 = 13.3$ and $E(B - V) = 0.04$, consistent with our determination above and our prior analyses of this cluster. In later sections, we will allow these quantities to vary in the fitting procedure, but we keep them fixed in this case because the uncertainties are small relative to our bin size.

Our atmosphere model colors are based on pure hydrogen atmosphere models from Tremblay et al. (2011), as a function of $T_{\text{eff}}$ and surface gravity. In the case of the WFC3 field, the $F336W$ data are the deepest (photometric errors <0.1 mag at a fainter position along the cooling sequence), and in the case of the ACS fields, the $F555W$ data are the deepest. Thus, we convert the $F336W$ and $F555W$ magnitudes to bolometric magnitudes using the above models. The assumption of a pure hydrogen atmosphere model for the hottest white dwarfs is questionable because it takes a finite time for the heavy elements to sediment out and for a star to take on the traditional onion-skin structure assumed for white dwarfs. Fortunately, the spectroscopic classifications of the SDSS hot white dwarfs from Krzesinski et al. (2009) clearly identify this transition, showing that DA white dwarfs appear for bolometric magnitudes $M_{1.5bol} >$. Thus, for magnitudes brighter than this, our bolometric magnitudes may be inaccurate, but the bulk of our sample is fainter than this.

To construct the bolometric LF in the outer fields, we must account for the effects of photometric incompleteness. We first count and bin observed stars as a function of $F555W$ to obtain a raw number count. In order to understand the incompleteness, we perform a Monte Carlo simulation in which we draw white dwarfs of the appropriate magnitude and then quantify their expected detectability using the results of the artificial star tests. This is sampled until the number of detections equals the observed raw number, and the number of drawn input stars required to meet this target yields an estimate of the true underlying number of white dwarfs of this magnitude in our field.

In the case of the LF in the core, we must also account for the fact that the density of sources varies across the field, and this leads to a covariance between incompleteness and location in the field. Our artificial star tests determine incompleteness as

![Figure 3](image-url)
a function of radius, and so we need to account for the radial profile of the underlying sources as well. Fortunately, 47 Tuc has been a subject of close study for many years, and the radial profile of stars is known to be well described by a King model with $W_0 = 8.6$ (McLaughlin et al. 2006). Our core field extends out to 2.7, and so we are able to measure a core radius for MS stars directly from our data, yielding $r_0 = 29.7 \pm 0.4$. This is within $2\sigma$ of that measured by Goldsbury et al. (2013) from surface density profiles.

The core radii of white dwarfs and main-sequence stars may not be the same, however, because of the mass loss associated with the latter stages of stellar evolution. The energy equipartition in such a dynamically relaxed system implies that lower-mass stars such as white dwarfs ($\sim 0.5 M_\odot$) should have a larger velocity dispersion and therefore larger radius than more massive main-sequence turnoff (MSTO) stars ($\sim 0.8 M_\odot$). Thus, our modeling needs to consider a range of possible core radii. Furthermore, there is a distinct possibility that the core radius may be a function of white dwarf luminosity. If the core relaxation time is longer than the timescale over which a star loses mass, then the hottest white dwarfs may still exhibit the core radius of their more massive progenitor population. This results in an intimate connection between the details of stellar evolution and the number counts of hot white dwarfs. If much of the mass is lost on the asymptotic giant branch, then the hottest white dwarfs may be overrepresented in the core relative to their cooler brethren, as they will still exhibit a smaller velocity dispersion.

Alternatively, if much of the mass is lost on the red giant branch, then we expect a smaller effect of this sort, because the stars will have spent $\sim 10^8$ years on the horizontal branch with a mass close to that of a white dwarf and so will have adjusted their velocity dispersion appropriately before ever becoming a white dwarf. Thus, we wish to examine a range of core radii ranging from one similar to the MS stars, up to $1.27 \pm 0.4$, based on a white dwarf mass of $0.53 M_\odot$ and an MSTO mass $\sim 0.86 M_\odot$ (e.g., Thompson et al. 2010).

The construction of our resulting empirical LF proceeds as follows when using the $F336W$ data, mapped onto bolometric magnitudes using the atmospheric models. In order to keep our results less sensitive to the modeling, we restrict our attention to radii from the core, in order to avoid uncertainties associated with the aforementioned dynamical adjustment. On these scales, the two-body relaxation time locally is $\sim 10^8 \text{yr}$ and therefore should not affect the LF at magnitudes appropriate to neutrino cooling. We count and bin observed stars as a function of $F336W$ to obtain a raw number count. In order to understand the incompleteness, we perform a Monte Carlo simulation in which we draw white dwarfs of the appropriate magnitude from the underlying King model, to form a radial profile, and then quantify their expected detectability using the results of the artificial star tests. This

Figure 4. Small open circles represent the observed white dwarf population in the core of 47 Tuc, observed with the WFC3 camera. The large red circles show the atmosphere model, for a white dwarf of mass $0.51 M_\odot$, distance modulus $\mu_0 = 13.2$, and $E(B - V) = 0.02$. These are chosen to represent the most plausible fit consistent with other determinations of distance. We see that the models fit the data well for $F336W < 23$ but are too blue relative to the data for fainter magnitudes. It is this mismatch that drives the best fits to lower distances.

6 The potential effects of dynamical relaxation are dealt with in more detail in Heyl et al. (2015).
is sampled until the number of detections equals the observed raw number and the number of drawn input stars required to meet this target yields an estimate of the true underlying number of white dwarfs of this magnitude in our field. The error bars are calculated by repeating the procedure for a range of potential core radii from 20″ to 40″ (to account for uncertainties in the cluster profile) and also by accounting for the Poisson fluctuations in the raw counts. In this manner, we define an empirical bolometric white dwarf LF in the core of 47 Tucanae while accounting for photometric scatter and uncertainties in the mass profile.

The resulting LFs from the two data sets are given in Table 1. Figure 5 also compares these two independent determinations with the LFs derived for the solar neighborhood from the SDSS by De Gennaro et al. (2008) and Krzesinski et al. (2009). In those cases, a correction for the number density of stars has to be made, so we have allowed for an overall normalization shift and have set the normalization so that the disk and cluster LF do not overlap exactly, to enable ease of visual comparison. The Krzesinski et al. (2009) LF is the only one that goes to bright enough magnitudes to provide a meaningful comparison with our data set. The precise number counts at the bright end of those data are somewhat uncertain because of several completeness effects related to the spectroscopic selection, as described in Krzesinski et al. and in Eisenstein et al. (2006). However, the ability to get spectroscopy of their stars allows them to classify stars according to spectral type, for which our stars are too faint. As noted above, genuine DA white dwarfs only appear at $M_{bol} > 1.5$ in the SDSS sample, as hotter white dwarfs have not yet had

Table 1: Bolometric Luminosity Functions for 47 Tucanae

| $M_{bol}$ | $F336W$ | $F555W$ |
|-----------|---------|---------|
|           | $N$     | $N'$    | $N$ | $N'$ |
| 0         | 1       | 1±1     | 0   | ... |
| 1         | 1       | 1±1     | 0   | ... |
| 2         | 2       | 2±2     | 0   | ... |
| 3         | 7       | 9±4     | 0   | ... |
| 4         | 8       | 10±5    | 3   | 3±3 |
| 5         | 20      | 27±3    | 12  | 13±3 |
| 6         | 41      | 58±12   | 21  | 23±3 |
| 7         | 89      | 133±18  | 72  | 81±10 |
| 8         | 269     | 417±39  | 214 | 251±18 |
| 9         | 513     | 845±74  | 279 | 390±26 |
| 10        | 809     | 1436±118| 405 | 551±33 |

Note. Under each bandpass we list the raw counts ($N$) in each bolometric magnitude bin and then the counts corrected for selection biases ($N'$) as described in the text. The error bars incorporate the effects of photometric scatter, incompleteness, and the radial density profile and are thus moderately larger than the nominal Poisson error. Note that the bolometric corrections for the brightest two bins ($M_{bol} < 1.5$) may be uncertain as these may be too young to be pure H atmospheres.

Figure 5. Filled circles indicate the bolometric function measured for the inner field using the WFC3 data, and the open circles indicate the equivalent measured using the ACS data in the outer fields. The similarity in the number counts is somewhat coincidental, resulting from the competing effects of lower stellar density but greater field coverage in the ACS data. Also shown, as triangles, are the equivalent LFs measured for the disk by SDSS, as presented by De Gennaro et al. (2008; open symbols) and Krzesinski et al. (2009; filled symbols). These densities have each been multiplied by an overall normalization factor to convert them to a number on this plot so that one can visually compare the resulting slopes.
sufficient time for gravitational settling to occur, and so our bolometric corrections are likely to be inaccurate for \( M_{bol} < 1 \). The slopes of the disk and cluster LFs compare well for \( M_{bol} > 5 \) though, with the exception of a possibly larger flattening observed in the ACS data for \( M_{bol} > 8 \). At these magnitudes, the scatter in the white dwarf sequence and the SMC main sequence begins to overlap, and the lower counts are possibly the result of white dwarfs being lost as a result of confusion with SMC main-sequence stars.

At the bright end, our LFs are consistent with a relatively smooth extrapolation of the slope at the fainter end toward higher luminosities. This contradicts the expectations based on the SDSS LF. If we normalize the Krzesinski et al. LF to ours at \( M_{bol} = 4 \), the SDSS data would predict 10–19 stars (depending on which SDSS LF binning is used) in the magnitude bin centered on \( M_{bol} = 2 \), whereas we count only two stars in this bin, a discrepancy of approximately 3\( \sigma \). Torres et al. (2014) have commented on the SDSS “plateau” and found that it could not be reproduced with standard models. Torres et al. examined a variety of possible explanations and concluded that the upturn cannot be the result of a feature in the Galactic inputs such as star formation rate variations. They further concluded that errors in the model colors, uncertain white dwarf cooling tracks, or statistical fluctuations were unlikely to be the cause. Their preferred solution was that the observed flattening was the result of erroneous mass determinations that led to some white dwarfs being assigned unrealistically low masses and consequently larger distances and larger inferred luminosities. All of our white dwarfs are at the same distance and have the same mass, since they follow a single cooling track, so that this selection effect should not influence this LF. The uncertainty in the bolometric corrections for the core data should also not affect this conclusion, because the bins are quite large, and any white dwarfs observed would be counted. In summary, the lack of any plateau in our data confirms the conclusion of Torres et al. that this is likely the result of systematic error rather than a physical effect. This is consistent with the behavior of the proper-motion-selected LF of Rowell & Hambly (2011) at the bright end (shown in Figure 3 of Rowell et al. 2013), which also drops monotonically, except for a spike at the brightest magnitudes, which may represent the presence of non-DA white dwarfs.

4. MODELS

In order to evaluate the role of various physical inputs into the cooling of white dwarfs, we need to match our observed LF to models for the rate of cooling. We have established an extensive framework for such modeling in previous papers on the cooling functions of cluster white dwarfs, most recently Hansen et al. (2007, 2013). However, our previous work has been devoted primarily to the coolest white dwarfs, and the focus on hot white dwarfs in this project necessitates the investigation of several relevant factors with greater care and detail than in our previous work.

Our default white dwarf cooling models are based on the code of Hansen (1999). For the purposes of this work, the most important part is the implementation of neutrino cooling, which is taken from the work of Itoh et al. (1996). The focus on young, hot, white dwarfs also requires greater attention to the starting conditions of stars that begin to descend the white dwarf cooling sequence. In order to establish a baseline starting model, we have used the MESA models (Paxton et al. 2011) to construct full evolutionary models of stars with initial masses ~0.9\( M_\odot \) and metallicity 0.004. Figure 6 shows the evolution of the central density and temperature for two stellar models of initial mass 0.9\( M_\odot \) and metallicity 0.004, both with (solid curve) and without (dashed curve) neutrino emission. The dotted contours indicate loci of constant neutrino emissivity. The two filled circles indicate the location at which the star reaches an effective temperature of \( 10^5 \) K, an approximate location for the start of the white dwarf cooling sequence. These curves indicate that a self-consistent treatment of neutrino cooling in the stellar evolution implies differences of a factor of two in the initial white dwarf central temperature. They also indicate that the dominant neutrino emission process of relevance here is plasmon emission. The change in slope of the dotted contours corresponds to the transition from emission due to photoneutrino production (left of the diagram) to plasmon decay (lower right). The white dwarfs are well into the latter regime.

We use these models as the reference model and consider variations in the input parameters in our cooling models to investigate the sensitivity to uncertain aspects of the physics.

The most obvious parameter of relevance is the total white dwarf mass. We consider a range of masses ~0.5–0.55\( M_\odot \). This is the mass range expected on theoretical grounds (e.g., Fusi-Pecci & Renzini 1976) and observed directly from the pressure broadening of spectra of hot cluster white dwarfs (Moehler et al. 2004; Kalirai et al. 2009). Modeling of the full white dwarf cooling sequence in this cluster and others (Hansen et al. 2007, 2013) also agrees with this estimate. In that case, the mass can be constrained directly because the observations contain mass information due to the fact that the onset of crystallization is mass dependent and so the cooling curves for different masses are not scaled versions of one another. The sample of white dwarfs observed here is too hot to have undergone crystallization, and so we restrict our analysis to the plausible mass range above identified by other means.

In addition, although we start with a reference model, there is also some uncertainty in the establishment of this baseline. The chemical composition of the white dwarf core is affected by prior evolution as the temperature history of the core, as well as uncertainties in the cross section of some nuclear reactions, will affect the relative abundances of carbon and oxygen and their profile through the core. We have studied this in detail using a range of stellar models, as detailed in the supplementary information of Hansen et al. (2013). These models also account for possible variations in the initial helium abundance of the star and uncertainties related to possible mixing of compositional gradients by Ledoux convection. Incorporating these uncertainties produces a range in central oxygen mass fraction of 0.64–0.86. The core composition proves to be much more important for the hot white dwarfs discussed here than for the cooler white dwarfs undergoing crystallization, because the neutrino emission is quite insensitive to the relative proportions of carbon and oxygen in the core. Furthermore, although the MESA models provide an initial temperature profile, with a central temperature of ~10^8 K with neutrino cooling and ~2 × 10^8 K without, we also allow for a variation of 10% in starting temperature to account for uncertainties in prior evolutionary stages.

We have also examined a range of helium and hydrogen layer masses. These lie at sufficiently low densities that they will not have an effect on the neutrino emission, but they can
contribute to the regulation of thermal diffusion of energy through the white dwarf and can therefore potentially affect the location of the transition from neutrino-dominated to photon-dominated cooling. Hydrogen layers can have two additional effects. The lower mean molecular weight of hydrogen means that the radius of the white dwarf can be non-negligibly affected by the thick hydrogen layer, at least for hot white dwarfs. This can change the location of the cooling sequence in the CMD and therefore affect the fit of the data. Furthermore, sufficiently thick hydrogen layers can result in a contribution to the luminosity from p–p nuclear burning, which can also change the cooling curve.

For young white dwarfs, it is also possible that the H and He layers have not completely gravitationally separated, which will change the opacity of the atmosphere and affect the cooling. This occurs near the surface of the white dwarf and will therefore have a negligible effect on the neutrino cooling, but it may affect the location where photon cooling dominates over neutrinos. We note, however, that we examine a large range of hydrogen and helium layer masses, and that the helium layer masses are an order of magnitude or more larger than the hydrogen layer masses. Thus, a surface layer of hydrogen diluted with helium can be considered the limiting case of a thin hydrogen atmosphere. We have considered H layer mass fractions as small as $q_H = 10^{-6}$ and find that our results are very insensitive to values of $q_H < 10^{-4}$. Thus, we believe that uncertainties in the separation of H and He do not affect our results. Figure 7 shows some examples of these different cooling curves.

4.1. Binary White Dwarfs

The WFC3 data are taken in the cluster core, and so any effects of binarity are likely to be increased owing to mass segregation. However, the hot white dwarf sequence observed here covers a very short-lived phase of stellar evolution, and so the observation of two hot white dwarfs in the same binary would require that the original binary pair had main-sequence masses within 1% of each other. If the mass ratio is determined by randomly sampling the Salpeter mass function, this occurs in $\sim 10^{-3}$ of pairs containing one MSTO star. Thus, even for relatively high global binary fractions, we do not expect a substantial contribution of binaries to this LF.

4.2. Nonstandard Neutrino Physics

There are many proposals for how modifications to the properties of the neutrino could point the way to physics beyond that contained in the standard model. One of the most prominent is the proposal that the neutrino may possess a nonzero magnetic dipole moment. Such a modification also has an effect on the plasmon neutrino cooling rate and is thus amenable to constraint in hot white dwarfs (e.g., Wang 1992; Blinnikov & Dunina-Barkovskaya 1994; Haft et al. 1994).
Figure 7. Solid curve shows the photon luminosity of a 0.53$M_\odot$ white dwarf with standard neutrino cooling. The corresponding model with no neutrino luminosity is given by the dotted curve. The dashed curve represents the same model except that we have increased the initial H layer mass.

Figure 8. Filled circles show the observed white dwarf cooling sequence in the ACS bandpass, while the red boxes indicate the grid used to bin the data and models for the purposes of a quantitative comparison.
We investigate the resulting extra cooling by considering the inclusion of an amplification factor for the plasmon neutrino emission from Haft et al. (1994),

\[
\epsilon_{\text{total}} \over \epsilon_{\text{standard}} = 1 + 0.318 Q \left( \frac{\mu_\nu}{10^{-12} \mu_\text{B}} \right)^2 \left( \frac{\hbar \omega_p}{10 \text{ keV}} \right)^{-2}
\]

where \( \mu_\nu \) is expressed in terms of the Bohr magneton \( \mu_\text{B} \) and \( \omega_p \) is the plasma frequency, given by

\[
\hbar \omega_p = 0.021 \text{ keV} \rho^{1/2} \left[ 1 + \left( \rho / 1.96 \times 10^6 \text{ g/cm}^{-3} \right)^{2/3} \right]^{-1/4}.
\]

\( Q \) is a function that depends on the underlying plasma properties but is \( \sim 1 \) to within 10% over the density and temperature range appropriate to the centers of white dwarfs.

### 4.3. Axion Cooling

Hot white dwarfs are a favorite astrophysical constraint on hypotheses of exotic particles, because such particles can cause extra cooling if they couple to nuclei, electrons, or photons. One commonly proposed extra cooling mechanism is emission of axions. The axion is a hypothetical particle (Weinberg 1978; Wilczek 1978) associated with the U(1) symmetry proposed by Peccei & Quinn (1977) as a solution to the strong CP problem of particle physics. If such axions couple to electrons, they can result in an increase in the luminosity of hot white dwarfs.

We can treat this by including an extra cooling contribution in the white dwarf models, of the form

\[
\epsilon_{\text{ax}} = 1.08 \times 10^{23} \text{ erg g}^{-1} \text{ s}^{-1} F(\rho, T) \frac{g_{ae} Z^2}{4\pi A T_7^4},
\]

where \( T_7 \) is the temperature measured in units of 10^7 K and \( F \) is the correction for ionic correlation effects from Nakagawa et al. (1987). The factor \( Z^2/A \) ranges from 3.6 to 3.8, depending on the core composition. The axion–electron coupling \( g_{ae} \) is related to the mass of the axion \( m_{\text{ax}} \) by

\[
g_{ae} = 2.8 \times 10^{-14} m_{\text{ax}}/1 \text{ meV (up to an unknown angle } \beta).\]

### 4.4. Radiation into Extra Dimensions

Some models of gravitation invoke a version of string theory that includes additional dimensions that are compactified on dimensions large enough to have experimental consequences (Arkani-Hamed et al. 1998). In such models, the coupling of photons, electrons, or nucleons to gravity can result in the emission of Kaluza–Klein gravitons into these extra dimensions, which will manifest themselves as an extra source of cooling for hot stars. Barger et al. (1999) present expressions for the emissivity for a variety of processes and place constraints on the mass scale \( M_s \) corresponding to extra dimensions by using astrophysical constraints from the Sun, red giants, and SN 1987A. Biesiada & Malec (2002) place additional constraints on this mass scale using the pulsational stability of the pulsating white G117-B15A and the fact that electron–graviton bremsstrahlung would accelerate the cooling.
We incorporate the emissivities of Barger et al. for three processes, namely, photon–photon annihilation, Gravi-Compton-Primakoff scattering, and gravibremsstrahlung. These are

\[ \epsilon_{\gamma\gamma} = 5.1 \times 10^{-9} \text{erg g}^{-1} \text{s}^{-1} T_7^2 \rho_6^{-1} \left( \frac{M_e^2}{1 \text{ TeV}} \right)^{-4} \]  

(4)

\[ \epsilon_{\text{GCP}} = 4.5 \times 10^{-6} \text{erg g}^{-1} \text{s}^{-1} T_7^2 \left( \frac{M_e^2}{1 \text{ TeV}} \right)^{-4} \]  

(5)

\[ \epsilon_{\text{GB}} = 5.8 \times 10^{-3} \text{erg g}^{-1} \text{s}^{-1} Z_7^2 T_7^4 \left( \frac{M_e^2}{1 \text{ TeV}} \right)^{-4}, \]  

(6)

where \( \rho_6 \) is the density in units of \( 10^6 \text{ g cm}^{-3} \), \( T_7 \) is the temperature in units of \( 10^7 \text{ K} \), and \( Z_7 \) is the mean ion charge relative to nitrogen (the values for our model mixtures of carbon and oxygen range from 7.2 to 7.8). We have assumed two macroscopic extra dimensions.\(^7\) These rates are calculated for nondegenerate material, although Barger et al. claim that corrections for degeneracy should be of order unity. In the case of the red giant cores considered in that paper, such an approximation may be acceptable, but it is likely to be an overestimate under the much more degenerate conditions appropriate to a white dwarf (a fact that does not appear to have been acknowledged by Biesiada and Malec). The latter two processes above depend on electron scattering, and therefore the rates should be considerably depressed in a white dwarf. Although a full rederivation of the rates is beyond this paper, we also test modified expressions for \( \epsilon_{\text{GCP}} \) and \( \epsilon_{\text{GB}} \) in which the rates are scaled by a factor of \( k T/E_F \), where \( E_F \) is the Fermi energy of the electrons. This limits the fraction of the electrons that participate to only those within \( k T \) of the Fermi surface, and which therefore are energetically able to scatter to a state that is not excluded by the Pauli principle. The resulting expressions are

\[ \epsilon_{\text{GCP}} = 2.3 \times 10^{-8} \text{erg g}^{-1} \text{s}^{-1} T_7^9 \rho_6^{-2/3} \left( \frac{M_e^2}{1 \text{ TeV}} \right)^{-4} \]  

(7)

\[ \epsilon_{\text{GB}} = 3 \times 10^{-5} \text{erg g}^{-1} \text{s}^{-1} Z_7^2 T_7^4 \rho_6^{-2/3} \left( \frac{M_e^2}{1 \text{ TeV}} \right)^{-4}. \]  

(8)

\(^7\) One extra dimension is excluded experimentally by confirmation of Newton’s gravitational force law and the model in three extra dimensions produces rates too low to be tested here.

**Figure 10.** Filled circles show the minimum \( \chi^2 \) at each value of \( f_s \), after marginalizing over white dwarf masses and values of \( q_{\text{He}} \) and \( q_{\text{H}} \), as well as distance and extinction. The dotted line shows the value of \( \Delta \chi^2 = 4 \) relative to the minimum, so that the dashed vertical lines indicate the region of 95% confidence. The slope is steeper for \( f_s < 1 \) than for \( f_s > 1 \), suggesting that the constraints on a modicum of extra cooling are weaker than models with less cooling.

4.5. Monte Carlo Model

Using the cooling curves constructed in this fashion, we simulate artificial white dwarf populations assuming that the birth rate of white dwarfs has been constant over the past \( 10^9 \) yr (since our comparison data set comprises ages \( \sim 10^8 \) yr at the faint end). For each white dwarf, the model provides a unique luminosity and effective temperature, which is converted into a magnitude and color based on a chosen value of distance and extinction. We then use the results of our radial density profiles and photometric scattering matrix to...
probabilistically assign output magnitudes and colors given the original input value, including the nondetection of stars. The resulting model populations are then binned in color and magnitude on the grid shown in Figure 8 and compared to the data binned in the same manner. Given the problematic colors for the core data, we restrict this analysis to the swathe of outer cluster fields observed with the ACS camera. The grid is chosen to provide sufficient color resolution to constrain the distance and extinction, while still maintaining enough points to ensure stability of the fitting procedure. The brightest bin covers 1 mag in range because the rapid cooling at these temperatures makes the counts insensitive to the cooling and more sensitive to initial conditions.

We restrict our attention to the stars with $F_{555} < 25.15$. Our limit is set by the increasing risk of confusion due to photometric scatter from the SMC main sequence in the background. We also account for this in our reddest bins by modeling the color spread of the SMC population as a function of magnitude. We extrapolate this model blueward with a Maxwellian function, using the fitted color dispersion, in order to anticipate the pollution of the white dwarf sequence with scattered main-sequence stars, and we include these in the model.

5. RESULTS

We compare our data with models calculated as described in Section 4, using the reference model from MESA and considering variations in initial temperature and core chemical composition. For each core model, the comparison with the data also requires a choice of distance modulus and extinction. These, combined with the parameters of white dwarf mass, and helium and hydrogen surface mass fractions, as well as an overall global normalization, imply a total of six parameters to be varied in the comparison of a particular model with the data. In all cases, we allow the distance modulus to vary from 13.0 to 13.5 and the reddening to vary from $E(B - V) = 0.0$ to 0.08. White dwarf masses are varied from $0.5M_\odot$ to $0.6M_\odot$, while helium and hydrogen mass fractions are varied from $q_{0.01He} = 0.01$ to 0.04 and $q_{11H} = 1 \times 10^{-6}$ to $6 \times 10^{-4}$.

The comparison between models and data is performed by binning on the grid shown in Figure 8. The brightest stars are assigned to a single large bin in order to lessen the sensitivity of our results to uncertainties in initial parameters. The principal goal of this comparison is to locate the magnitude at which the cooling rate changes as a result of the transition to photon-dominated cooling from other processes, be it via neutrinos or more exotic processes. The color binning is chosen to constrain the location of the cooling sequence in color and thereby measure the extinction simultaneously with the cooling. The final grid thus contains 47 bins, so that comparison with a particular core model has 40 degrees of freedom. The best fit for a model with our standard neutrino cooling yields $\chi^2 = 44.8$ for $0.53M_\odot$, a helium layer mass fraction $q_{He} = 0.037$, and $q_{H} = 4 \times 10^{-4}$. This hydrogen layer is slightly larger than usually assumed, but not so large that residual hydrogen burning is a major contributor. Larger masses ($q_{H} > 6 \times 10^{-4}$) yield poor fits ($\chi^2 > 100$) because the nuclear contribution dramatically changes the shape of the cooling curve, indicating that the cooling of the

![Figure 11](image-url)

Filled circles represent the same observed counts as in Figure 9, but the red histogram is now the best-fit model for the case of no neutrino cooling. We see that the requirement that the model fit the data at the faint end results in a large overestimate of the number of bright white dwarfs.
white dwarfs in 47 Tuc is not being substantially delayed by residual H burning, as has been suggested for lower-metallicity progenitors (Miller Bertolami et al. 2013). The best-fit distance modulus is $\mu_0 = 13.27$, which compares well with other distance estimates, although the best-fit reddening, $E(B - V) = 0.08$, is at the red end of the allowed range. Figure 9 shows the comparison of the model with the data. In this plot, we show the counts as a function of color in each luminosity bin (separated by vertical dotted lines). For instance, the five bins between the dotted lines indicating $F555W = 24.1$ and 24.25 show the counts in five color bins spanning $F435W - F555W = -0.1$ to 0.15. This projection of the two-dimensional data into a pseudo-LF allows us to assess the quality of the model fit to the data.

We test the sensitivity of our results to the neutrino emission by applying a uniform scaling factor $f_s$ to the neutrino emission and redoing the fit, marginalizing over the white dwarf mass, internal composition, and layer masses, as well as distance modulus and extinction ranges described above. The resulting curve of $\chi^2$ as a function of $f_s$ is shown in Figure 10. At 95% confidence, $0.6 < f_s < 1.7$, with the bestfit $\chi^2$ achieved for $f_s \sim 0.9$. The value at $f_s = 1$ is only $\Delta \chi^2 = 0.5$ larger than the minimum, so that the difference is not statistically significant. Thus, our white dwarf cooling models favor the traditional implementation of neutrino emission and constrain variations to be approximately within a factor of two. There is also no indication that increased neutrino cooling can be offset by nuclear burning in a thick H envelope.

The $f_s$ scaling models all start with the initial conditions determined from the MESA models, but we noted in Section 4 that a self-consistent evolutionary model with no neutrinos would begin with a higher central temperature, so we have also tested a model with no neutrino cooling starting with the appropriate initial conditions. The best fit is achieved for a $0.55M_\odot$ model with $q_{He} = 0.025$ and $q_{H} = 2 \times 10^{-4}$. The best-fit distance and extinction are $\mu_0 = 13.16$ and $E(B - V) = 0.08$, respectively. Nevertheless, the minimum $\chi^2 = 184$, which is very poor compared to our best-fit model. Figure 11 shows this model and demonstrates, when compared with Figure 9, how these data discriminate between models. In this case, the lack of neutrino cooling results in slower early cooling and an excess of counts at bright magnitudes relative to faint magnitudes.

These results also allow us to anticipate a comparison with constraints on neutrino emission from the pulsational stability of hot DBV white dwarfs (Winget et al. 2004). Bischoff-Kim (2008) provides a model for the pulsational properties of the hot DBV star EC20058-5234 and predicts the rate of change of two pulsational periods as a function of $\lambda$ (scaled explicitly relative to the plasmon neutrino rate in that case, but effectively the same as our overall scaling parameter $f_s$ in this regime). Based on our constraints above and the figures in Bischoff-Kim (2008), we anticipate that the period derivatives of the 257 s and 281 s modes in that star should be within $1.0 \pm 0.4 \times 10^{-13}$ s/s and $1.4 \pm 0.5 \times 10^{-13}$ s/s, respectively.

5.1. The Neutrino Magnetic Moment

The restriction on scaled neutrino emissivities should then also translate into constraints on exotic radiation mechanisms.
The constraint \( f_e < 1.7 \) can be used in Equation (1) to obtain an approximate limit \( \mu_f < 5 \times 10^{-12} \mu_B \). A more accurate limit is obtained by repeating the cooling calculations using the correction to the emissivity given by Equation (1), including the density dependence. If we repeat the fitting procedure with these models, marginalizing again over distance, extinction, and white dwarf mass parameters, we find that the 95% confidence limit on the neutrino magnetic moment is \( \mu_\nu < 3.4 \times 10^{-12} \mu_B \).

This limit is an order of magnitude better than the current laboratory limits \( \sim 3 \times 10^{-11} \mu_B \) (Daraktcheva et al. 2005; Arpesella et al. 2008; Beda et al. 2010) and also better than astrophysical limits based on the lifetime of the Sun (Bernstein et al. 1963; Raffelt 1999) and horizontal branch stars (Raffelt et al. 1989). Most directly, it represents a factor of several improvement of earlier determinations \( \mu_{12} < 10 \) based on the hot white dwarf LF (Blinnikov & Dunaia-Barkovskaya 1994). Although measurements of the hot white dwarf LF have improved since then, the excess counts at the bright end (see discussion in Section 3.1) have hampered the statistical significance of such constraints using the more up-to-date data (Miller Bertolami 2014). Our measurement is also comparable to the limits derived from the core mass of red giant stars (Raffelt 1990; Raffelt & Weiss 1992; Castellani & degl’Innocenti 1993; Haft et al. 1994; Catelan et al. 1996; Viaux et al. 2013) but has the advantage of being measured in stars whose properties are dominated by the neutrino emission and in a manner in which the distance (the largest source of error in the red giant measurements) is constrained simultaneously.

In addition to the consequences for particle physics, a neutrino magnetic moment in the range \( \mu_{12} \sim 20–50 \) could lead to qualitatively different late-time evolution for stars in the initial mass range \( \sim 9–17M_\odot \) (Heger et al. 2009). However, our limit here appears to preclude this eventuality.

5.2. The Axion Mass

In a similar fashion, models with additional cooling due to axion emission, given by Equation (3), can be compared to the data to obtain a 95% confidence limit of \( g_{\text{ne}} < 8.4 \times 10^{-14} \), which implies an axion mass \(<4.1\) meV.

This constraint contradicts the claim of Corsico et al. (2012), whose modeling of the pulsating white dwarf G117-B15A implied that the default rate of cooling was too slow to match the observed rate of change of the pulsation period. They invoked an extra cooling due to axion emission that implied an axion mass of \( m_{\text{ax}} = 17.4^{+2.2}_{-1.7} \) meV, a 5.8σ discrepancy with respect to our limit. However, the Corsico result was based on the rate of change of a particular oscillation mode that they claimed was trapped in the hydrogen envelope. The trapping strongly slows the expected rate of period change and suggests that future improvements in the asteroseismological modeling with untrapped modes may better match the observations.

Figure 12 shows the best-fit solution for the case of a 17 MeV neutrino (with a distance \( d_B = 13.21 \) and \( E(B - V) = 0.08 \)). A comparison with Figure 9 demonstrates how too much cooling adversely affects the model fit—namely, that the counts at brighter magnitudes are now too low with respect to fainter magnitudes (the opposite trend seen in Figure 11).

Our limits are not consistent at the 95% confidence level with the proposal that an axion mass of \( \sim 5 \) meV is motivated by the overall behavior of the hot white dwarf LF (Isern et al. 2008). Caution has been expressed about this result by Miller Bertolami et al. (2014), who note that the strength of this conclusion varies depending on which observational LF is used, and is further muddied by the aforementioned uncertainties in the bright LF. Our results do not require such an axion, as the inclusion of axion cooling only worsens the fit of the model, but are not strong enough to conclusively rule it out.

5.3. Radiation into Extra Dimensions

Testing models that include radiation into extra dimensions place a 95% limit on the mass scale \( M > 0.54 \) TeV/c² when we include our ad hoc corrections for degeneracy (ignoring the degeneracy correction increases this to 0.9 TeV/c²). The limits are different because the steep temperature dependence of \( c_{\gamma\gamma} \) means that this rate is irrelevant even for our hot white dwarfs and only becomes important at energies corresponding to supernova cores, so that the cooling of the white dwarfs is indeed regulated by the processes that depend on electron scattering. These expressions are comparable to constraints based on the properties of the Sun but weaker than those based on red giants and supernovae (Barger et al. 1999; Cassisi et al. 2000). They are also weaker than the constraint derived by Biesiada & Malec (2002), although that estimate is likely overstated because the rates were not corrected for the effects of degeneracy.

6. CONCLUSION

Our results suggest that the cooling of hot white dwarfs is currently well understood. The bolometric LF we infer from our hottest stars shows a monotonic decrease to the highest effective temperatures observed and does not display the plateau observed in some prior studies. This supports recent claims that this feature was the result of systematic uncertainties rather than the consequence of unanticipated physical effects.

However, our observations in the core of the cluster result in a problematic match between the data and the models, in the sense that the model colors appear too blue relative to the data at fainter magnitudes. This suggests that either the photometric calibrations are systematically biased by the crowding of the field or the short-wavelength opacities are not fully understood for white dwarfs of effective temperatures \( \lesssim 19,000 \) K.

The atmospheric models do fit the data for the outer cluster fields, observed in longer-wavelength bandpasses. We fit detailed cooling models to the number counts in these fields, which provide an excellent match to the observations without requiring any substantial modifications to the physics. Indeed, the comparison suggests that the neutrino emission models of Itoh et al. (1996) are accurate to within a factor of two (at 95% confidence). This match can also be used to constrain a variety of proposals for additional exotic cooling mechanisms and provides constraints on the existence of a neutrino magnetic moment, emission of axions, and possible radiation of energy into extra dimensions. In each of these cases, the inclusion of extra cooling makes the fit to the data worse and provides little evidence for any exotic physics.

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