EMPLOYING A NEW, $BVI_{c}$ PHOTOMETRIC SURVEY OF IC 4665 TO INVESTIGATE THE AGE OF THIS YOUNG OPEN CLUSTER

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ABSTRACT

We present a new, $BVI_{c}$ photometric survey of the young open cluster IC 4665, which improves on previous studies of this young cluster by incorporating a rigorous standardization procedure, thus providing high-fidelity colors and magnitudes for cluster members. We use this new photometric dataset to reevaluate the properties (age and distance) of IC 4665. Namely, using a statistical approach incorporating $\tau^{2}$ color–magnitude diagram modeling, we measure a pre-main-sequence (PMS) isochrone age and distance of $36 \pm 9$ Myr and $360 \pm 12$ pc, as well as an upper-main-sequence turn-off age and distance of $42 \pm 12$ Myr and $357 \pm 12$ pc. These ages and distances are highly dependent on the isochrone model and color used for the fitting procedure, with a possible range of $\sim 10–20$ Myr in age and $\sim 20$ pc in distance. This spread in calculated ages and distances seen between colors and models is likely due to limitations in the individual membership catalogs and/or systematic differences in the predicted stellar parameters from the different sets of models. Interestingly, when we compare the isochrone ages for IC 4665 to the published lithium depletion boundary (LDB) age, $28 \pm 5$ Myr, we observe that this cluster does not appear to follow the trend of isochrone ages being 1.5 times smaller than LDB ages. In addition, comparing the overall magnetic activity (X-ray and Hα emission) in IC 4665 with other well-studied open clusters, we find that the observed activity distributions for this young cluster are best characterized by assuming an age of 30–40 Myr, thus in agreement with our PMS and turn-off isochrone ages for IC 4665. Overall, although some age discrepancies do exist, particularly in the ages measured from PMS isochrones, the range of possible IC 4665 ages derived from the various dating techniques employed here is relatively small compared to that found for other well-studied open clusters.

Key words: open clusters and associations: general – open clusters and associations: individual (IC 4665) – stars: evolution – stars: fundamental parameters

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Open clusters have long provided necessary empirical constraints for our current models of stellar evolution due to their large collection of coeval, equidistant, and chemically homogeneous stars. Through observations of large numbers of open clusters with known ages, we are able to investigate the manner in which fundamental stellar properties evolve as stellar evolution progresses. This is particularly true for early stellar evolution (stellar ages $< 100$ Myr), when fundamental physical parameters of stars change rapidly (e.g., radius, temperature, rotation rate, magnetic field strength). However, for these clusters to be used as valuable fiducial benchmarks of stellar evolution, we must be able to date them in a consistent manner with high-fidelity and precision. Currently, there are several dating methods utilized to determine open cluster ages, including fitting theoretical model isochrones to empirical H–R diagrams, light element abundance distributions, and exploiting the connection between magnetic activity and age.

A heavily relied upon approach to determining absolute ages of star clusters is finding a best-fitting color–magnitude diagram (CMD) isochrone for the nuclear turn-off (Sandage 1958; Mermilliod 1981a, 1981b; Meynet et al. 1993) and/or the pre-main-sequence (PMS) turn-on (D’Antona & Mazzitelli 1997; Baraffe et al. 1997; Siess et al. 2000) to the cluster’s main sequence, typically performed using an ad hoc “by-eye” comparison of the model isochrone to the observational photometric data. This technique, however easily applied in theory, is in practice commonly hampered by uncertainties including field star contamination, cluster distance, and/or photometric error. Furthermore, this technique suffers from the measured cluster ages being heavily dependent on the input physics used by the stellar evolution models. For instance, one can show for the same cluster that different nuclear turn-off and PMS models can give stellar ages that differ by a factor of 1.5–2 (Chiosi et al. 1992; Meynet et al. 1993; Meynet & Maeder 1997, 2000; Baraffe et al. 1998, 2002; Siess et al. 2000; Naylor 2009).

Several alternative dating techniques now exist which employ other observable properties of stars to find absolute and relative ages for open clusters. Observations have shown that the level of magnetic activity, indicated by the presence of X-ray and/or chromospheric activity, in solar-type stars clearly decreases with increasing age (Wilson 1963; Skumanich 1972; Noyes et al. 1984; Soderblom et al. 1991; Mamajek & Hillenbrand 2008; Cargile et al. 2009). This relationship is fundamentally tied to the interplay between magnetic activity and the rotationally induced, magneto-hydrodynamic dynamo in solar-type stars. This causal relationship, the so-called age–rotation–activity paradigm, generally holds true; however, it can be affected by natural activity cycles, similar to those seen in the Sun. For instance, Soderblom et al. (1991) show that uncertainties in stellar chromospheric ages can be as large as 50% for individual stars. Of course, in open clusters this error can be statistically reduced by measuring many stars.

IC 4665 is currently one of only a handful of well-studied PMS open clusters (i.e., age of 5–50 Myr), e.g., NGC 2169 (10 Myr; Jeffries et al. 2007), NGC 2547 (35 Myr; Jeffries & Oliveira 2005), and IC 2391 (50 Myr; Barrado y Navascués et al. 2005).
IC 4665 is a relatively young (< 100 Myr), nearby (~350 pc) open cluster in the constellation Ophiuchus (R.A.(2000): 17h46m, decl.(2000):+05°43'). The WEBDA Open Cluster Database³ reports for the cluster an age of 43 Myr, a distance of 365 pc, a high Galactic latitude (b = +17 deg), and has a reddening of $E(B-V) = 0.174$ (values originally published in Dias et al. 2002). The youth and close proximity of this cluster has made it a popular target for studying stars during early times, while the majority of its low-mass members are still in the PMS phase.

2.1. Extant Observations of IC 4665

Previously, the most extensive optical survey of IC 4665 was performed by Prosser (1993), which included astrometric, photometric, and spectroscopic programs to identify members of the cluster. P93 acquired $BVRI_\text{c}$ CCD photometry for 4100 stars down to a limiting magnitude of $V \sim 18.5$. Proper motions were measured from archival photographic plates and membership probabilities were derived for stars brighter than $V \sim 14.5$. Their analysis found 170 stars with non-zero proper motion membership probability, of which 22 were identified as previously known cluster members, 57 were classified as photometric candidates (i.e., stars lying near a 36 Myr isochrone), 72 photometric nonmembers, and 22 stars left with undecided membership. They also obtained low-dispersion spectra for 41 faint candidate stars, of which 25 showed definite Hα emission while five showed possible weak Hα emission. P93 include these 30 stars as probable members of IC 4665.

Multiple investigations into chromospheric and coronal activity have been conducted in IC 4665. Hα emission, as an indicator of chromospheric activity, has also been observed in 14 F-, G-, and K-spectral-type stars (Martin & Montes 1997), as well as for 39 lower-mass, M-spectral-type stars (P93). More recently, Jeffries et al. (2009a) measured Hα equivalent widths (EW) for 56 IC 4665 stars ranging from early-F to mid-M spectral type. In addition to chromospheric studies, IC 4665 also has been observed with the ROSAT X-ray telescope, in order to detect coronal X-ray emission. Giampapa et al. (1998) reported the results of a 76.9 ks exposure of the cluster with the High Resolution Imager instrument on ROSAT, from which they found 28 X-ray detections matching optical counterparts in the P93 catalog. Six of these 28 X-ray sources were shown to be cluster nonmembers by Giampapa et al. (1998) based on spectral-type classifications.

IC 4665 is currently one of just five open clusters with a detected lithium depletion boundary (hereafter LDB). Manzi et al. (2008) measured an age of 28 ± 5 Myr for the cluster based on the absolute magnitude of stars found at the LDB. Moreover, the global lithium abundance distribution in IC 4665 stars was first studied by Martin & Montes (1997), where they measure the Li abundance of 14 early-G through early-M spectral-type stars. Interestingly, they found that the Li distribution of IC 4665 is similar to the older Pleiades open cluster (~125 Myr), although they had a limited sample size of measured Li abundances. More recently, Jeffries et al. (2009a) determined the Li abundance of 20 late-F to early-M spectral-type stars and confirmed that the Li distribution of IC 4665 appears more like the Pleiades than other younger open clusters.

The stellar rotation distribution of IC 4665 is commonly used to empirically constrain theories of early angular momentum evolution (e.g., Barnes 2003, 2007). Using rotation period measurements for nine solar-type stars (F9 to K0 spectral type), Allain et al. (1996) find that there is a dearth of slow rotators (periods ≥ 4 days) in IC 4665, indicative of a young cluster where the stars have not had time to spin down. However, Jeffries et al. (2009a) measure projected rotation velocity (Vsin$i$) for IC 4665 cluster members and find that there is a lack of fast rotators (Vsin$i$ > 20 km s⁻¹) with $1 < (V - I_c) < 2$ (K-type stars). Comparing this Vsin$i$ distribution to the older IC 2391, IC 2602, and Pleiades, they find that the K-type stars in IC 4665 appear to rotate more slowly than one would expect at ~30 Myr. Finally, a recent survey reported rotation periods for 20 IC 4665 members with masses < 0.5 M⊙ (Scholz et al. 2009). They show that all of these low-mass stars are rotating rapidly (period ≤ 1 day), a finding similar to studies of other PMS clusters (e.g., Irwin et al. 2008).

2.2. New SMARTS BVIc Observations

We observed IC 4665 using the 1.0 m SMARTS telescope (the old YALO telescope) situated at the Cerro Tololo Inter-American Observatory (CTIO), Chile, during the nights of 2005 September 15, 16, and 17. The data were acquired with the quad-amplifier Y4KCam CCD camera, equipped with Johnson–Cousins BVIc filters, with its 15 μm pixels and 0′′289 pixel⁻¹ plate scale results in an on-sky field of view per CCD field of 19′3 × 19′3. Nine fields were observed covering a uniform grid of a 3 × 3 mosaic of CCD fields covering approximately 1 deg², centered on R.A.(2000):17h46m13.5 and decl.(2000):+05°41′52″. We employed exposure times of 100, 50, and 25 s for the B-, V-, and Ic-band observations, respectively. The central coordinates of each IC 4665 field for which BVIc photometry was obtained are shown in Figure 1 and summarized in Table 1.

³ The WEBDA database, developed by J.-C. Mermilliod, can be found at http://www.univie.ac.at/webda/.
All science and standard star images were processed for overscan region subtraction, master-bias subtraction, and flat fielding, using twilight sky images, using standard procedures in the IRAF\(^4\) suite of data reduction algorithms. Substantial use was also made of two batch processing IRAF scripts, written by Phil Massey of Lowell Observatory, whose protocol specifically handles the FITS headers and quad-amplifier readout of the CCD camera. The relatively low space density of the cluster, and its lack of substantial field crowding, allows us to employ aperture photometry for both IC 4665 science and standard star images. Source searching and aperture photometry, with an aperture radius of 13 pixels, were achieved using the DAOPHOT package in IRAF (Stetson 1987, 1992).

Equatorial \(BVI\) standard stars cataloged in Landolt (1992, 2009), with a broad dynamic range of photometric magnitude and color, and located at wide distribution of airmass, were observed nightly in order to correct for atmospheric extinction and to transform extinction corrected, instrumental magnitudes onto the standard system. Modified forms of Bouguer’s law, see Equations 1(a)–1(d), were used to define the relationship between standard and instrumental magnitudes for the standard stars.

\[
V = v + e(B - V) + \xi_v - \kappa_v X, \quad (1a)
\]
\[
V = v + e(V - I_c) + \xi_v - \kappa_v X, \quad (1b)
\]
\[
(B - V) = \mu(b - v) + \xi_{bv} - \mu \kappa_{bv} X, \quad (1c)
\]
\[
(V - I_c) = \psi(v - i_c) + \xi_{vi} - \psi \kappa_{vi} X, \quad (1d)
\]

where \(V\), \((B - V)\), and \((V - I_c)\) are magnitudes/indices on the \(BVI\) standard system; \(v\), \((b - v)\), and \((v - i_c)\) are measured, instrumental magnitudes/indices; \(\kappa_v, \kappa_{bv},\) and \(\kappa_{vi}\) are filter-dependent extinction coefficients; \(e, \mu,\) and \(\psi\) are color transformation coefficients; \(\xi_v, \xi_{bv}\), and \(\xi_{vi}\) are zero-point coefficients; \(X\) is the airmass of target—\(\approx\) see \(z\), where \(z\) is the zenith distance.

Unknown extinction coefficients, color transformation coefficients, and zero points were determined by solving the self-similar series of linear simultaneous algebraic equations detailed in Equations 1(a)–1(d). Solutions were derived using a least-squares fit algorithm\(^5\) which processes the numeric parameters via an iterative refinement method. Comparing calculated magnitudes and colors of Landolt standard stars to their published values allows an iterative rejection process to take place, thereby eliminating seriously discrepant standard star measurements—of which there were few. Solutions to the color equations for each observing night are listed in Table 2, whereby these solutions resulted in differences between calculated and published magnitudes of Landolt standard stars that were never greater than 2.2\% (i.e., 0.022 mag). Target star photometry was readily determined by substituting the derived extinction, transformation, and zero-point coefficients along with measured instrumental magnitudes into Equations 1(a)–1(d).

The full \(BVI\) catalog for all IC 4665 fields is provided in Table 3, including their associated \textsc{2mass} \(J, H,\) and \(K_s\) photometric and astrometric data, correlated with point sources in the online \textsc{2mass} database (Skrutskie et al. 2006). Of the 7359 stars in our master \(BVI\) catalog, we find 452 stellar sources without matches within 3\% of \textsc{2mass} sources. For these stars, we provide \textsc{jwst} astrometry, precise to \(\pm 1\)", using a sixth-order polynomial fit to \(X,Y\) CCD coordinates and accurate and precise coordinates for reference stars in the \textsc{superCOSMOS} catalog (Hambley et al. 2001). A visual presentation of the \(BVI\) photometric catalog is shown in Figure 2, in which we plot \(V\) versus \(B-V\) and \(V-I_c\) CMDs in concert with D’Antona & Mazzitelli (1997) fiducial isochrones.

In order to investigate the stability of our photometric system, we also observed a control field (CF) in IC 4665 during the nights

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\(^4\) IRAF, in our case through http://iraf.net, is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^5\) The algorithm, F04AMF, is distributed by the Numerical Algorithms Group (NAG).
of the 2005 September 15 and 17. Figure 3 shows our $V$, $B$, and $I_c$-band magnitude comparisons for stars in common to the CFs observed on the two different nights. A simple statistical analysis of these data is presented in Table 4. From these plots and table, we can infer that the $V$- and $I_c$-band zero points are at least consistent at the level of $\pm 3\%–4\%$ for objects with $V$ and $I_c < 16$ mag. For these same objects, the $B$-band observations do however show an offset at the $\pm 5\%–6\%$ level. Naturally, for the dimmer objects ($V$, $B$, $I_c > 16$ mag), with decreasing signal-to-noise levels, diminished precisions of order $\sim 9\%–10\%$ are seen.

2.3. Comparison to Prosser (1993) Photometry

Existing studies reporting on the physical characteristics of IC 4665 solar-type stars are under-pinned on the P93 photometry study, and it is therefore imperative that we determine the reliability of their photometric system as compared to ours. A detailed examination of the standardization procedure of P93

| Date          | Equation | Extinction$^a$ | CTC$^b$ | Zero Point | Mean$^c$ | rms | No. of$^d$ |
|---------------|----------|---------------|---------|------------|----------|-----|------------|
|               |          | Coefficient   |         |            | Δ mag    |     | Standards  |
| 2005 Sep 15   | $V(B-V)$ | 0.1478        | 0.0140  | $-1.8654$  | $6.3 \times 10^{-5}$ | 0.0148 | 90, 72     |
|               | $V(V-I_c)$ | 0.1560       | 0.0128  | $-1.8541$  | $1.0 \times 10^{-5}$ | 0.0176 | 87, 75     |
|               | $B-V$    | 0.1116        | 0.8940  | $-0.3011$  | $4.5 \times 10^{-5}$ | 0.0166 | 90, 71     |
|               | $V-I_c$  | 0.1235        | 1.0009  | 1.0472     | $1.0 \times 10^{-5}$ | 0.0172 | 89, 58     |
| 2005 Sep 16   | $V(B-V)$ | 0.1476        | 0.0166  | $-1.8518$  | $2.4 \times 10^{-5}$ | 0.0157 | 80, 62     |
|               | $V(V-I_c)$ | 0.1492      | 0.0171  | $-1.8524$  | $1.0 \times 10^{-5}$ | 0.0170 | 74, 62     |
|               | $B-V$    | 0.1497        | 0.8731  | $-0.2334$  | $7.5 \times 10^{-5}$ | 0.0177 | 80, 60     |
|               | $V-I_c$  | 0.0832        | 1.0001  | 0.9935     | $6.5 \times 10^{-5}$ | 0.0172 | 80, 60     |
| 2005 Sep 17   | $V(B-V)$ | 0.1556        | 0.0272  | $-1.8307$  | $8.1 \times 10^{-5}$ | 0.0180 | 76, 57     |
|               | $V(V-I_c)$ | 0.1574      | 0.0239  | $-1.8290$  | $-5.0 \times 10^{-5}$ | 0.0183 | 76, 57     |
|               | $B-V$    | 0.0460        | 0.8808  | $-0.3565$  | $-7.7 \times 10^{-5}$ | 0.0220 | 64, 52     |
|               | $V - I_c$ | 0.0163        | 1.0040  | 0.9107     | $3.3 \times 10^{-5}$ | 0.0190 | 74, 54     |

Notes.

$^a$ In units of magnitude/airmass.

$^b$ Color transformation coefficient.

$^c$ Observed mean difference between calculated and published magnitudes or colors for Landolt (1992, 2009) standard stars.

$^d$ Observed rms difference between calculated and published magnitudes or colors for Landolt (1992, 2009) standard stars.

$^e$ $m$, $n$—where $m$ is the number of Landolt standard stars observed and $n$ represents the number of standard stars used in the final photometric solution.
Figure 2. CMDs for our full photometric catalog are plotted (black dots). Also provided are D’Antona & Mazzitelli (1997) isochrones (blue dotted line) for the cluster’s LDB age (27.8 Myr; Manzi et al. 2008) and HIPPARCOS distance (355 pc; van Leeuwen 2009).

(A color version of this figure is available in the online journal.)

Figure 3. Comparison of CTIO BVI_c photometry for CFs in IC 4665, based on observing nights 2005 September 15, 16, and 17. Upper panels show direct comparison, while their residuals are plotted in each lower one. Data are plotted with their associated photometric error. Red dotted lines are loci of equality and not fits to the data.

(A color version of this figure is available in the online journal.)

shows that although nightly standard stars were used to derive extinction coefficients and color-transformation equations, the zero points of their BVI_c photometric system are tied to a solitary blue, high-mass B9e star. This star, HD 161261, has subsequently been found to have V-band variability on the order of 0.1 mag (Kazarovets & Samus 1997), which maybe due to a binary component (Pourbaix et al. 2004), as well as an infrared excess typical of rapidly rotating Be stars (Yudin 2001). Not surprisingly, we observe systematic offsets between the P93 photometry and our own that are likely a result of this extrapolation of standardized photometry derived from such a single, blue, possibly variable and binary standard star.

For stars in common to both catalogs, we plot in Figure 4 comparisons between the P93 study and our own V, B−V, and V−I_c photometric datasets. We translated the P93 Kron V−I colors to the Cousins system using the formalism given in Bessell & Weis (1987). We see a significant amount of scatter in the P93 photometry (∼0.1 mag in V; ∼0.2 in B−V/V−I_c) compared to our optical catalog. In addition, there appears to be a systematic offset of ∼0.05 mag in V, B−V, and V−I in the faintest/reddest P93 objects. Such a magnitude of photometric scatter and systematic offset may cause significant problems when trying to calibrate both color and magnitude relationships for stars in IC 4665; therefore, for the purpose of this paper, we will preferentially employ our, new BVI_c photometry in all subsequent analysis.
3. THE AGE OF IC 4665

Determining a precise and accurate age for IC 4665 is fundamental to its use as a constraint, or boundary condition, for theoretical models describing early stellar evolution. Its age, however, continues to be a matter of uncertainty. Ages for IC 4665 found in the literature range from greater than 25 to less than 100 Myr, although one of the age determinations is derived using the LDB method (Manzi et al. 2008), which so far has only been applied to a small handful of open clusters. With such a large range of possible ages cited for IC 4665, its applicability for constraining theoretical stellar evolution models remains suspect. Here, we use our new photometric data for cluster members of IC 4665 to take a new look at its discrepant age determinations to verify whether there exists a true, observational-dependent age spread in IC 4665, or whether this spread in ages is due to uncertainty in the extant studies of the clusters.

3.1. Pre-main-sequence Age

In the P93 study, the authors reported that they were unable to determine the age of IC 4665 from the location of the low-mass PMS, due to the lack of a defined low-mass sequence in their CMD. This may have been the result of systematic scatter in their photometry and/or their cluster membership determination being based on unreliable proper motion data. More recently, the infrared study of IC 4665 by de Wit et al. (2006) suggests that the cluster has an age of 50–100 Myr based on the location of its low-mass cluster sequence. However, de Wit et al. note that an accurate age for the cluster is difficult to measure due to the large amount of field star contamination present in their survey.

A quick examination of the full IC 4665 CMD reveals that we too confirm that an accurate fit of the cluster sequence is particularly difficult to achieve due to field star contamination in our CMD (see Figure 2). While IC 4665 lies relatively far from the Galactic plane ($b = +17^\circ$) the level of contamination along the CMD suggests that there is a high stellar density in the cluster’s line of sight through the Galaxy. In order to account for the field star contamination in the IC 4665 CMDs, we further constrain our analysis to those stars having ancillary membership indicators from a disparate range of extant photometric and spectroscopic observing campaigns. In the first instance, we positionally matched our photometric catalog with data from the following sources: three catalogs of stars with common kinematic properties (proper motions—P93; radial velocities—Prosser & Giampapa 1994; Jeffries et al. 2009a), stars with X-ray emission (Giampapa et al. 1998), two catalogs of stars with significant lithium absorption (Martin & Montes 1997; Jeffries et al. 2009a), three catalogs of stars exhibiting strong Hα emission ($EW_{\alpha H} > 0$ Å—P93; Martin & Montes 1997; Jeffries et al. 2009a), and finally, two catalogs of stars with short rotation periods in the region of IC 4665 (Allain et al. 1996; Scholz et al. 2009). X-ray and Hα emission (coronal and chromospheric), the presence of lithium in stellar photospheres, and rapid rotation are all indicators of youth for low-mass stars, and therefore we can exploit such surveys in order to segregate young cluster members from the typically much older field star populations. In Figure 5, we plot the CMDs with stars identified from the various membership catalogs. We will subsequently exclude proper-motion-selected members from our cluster catalog due to the lack of a clear (pre-)main-sequence in its CMD (see Figure 5, top panels), namely, proper motion must be an extremely poor membership criterion for this cluster. This can be explained by the similarity of the cluster’s systemic proper motion to that of the general field population, justifying the exclusion of the cluster’s proper motion catalog from all subsequent analysis of IC 4665 (see Jeffries et al. 2009a).

We recognize that the membership catalogs cited above contain varying levels of field contamination, as well as biases based on their color and/or magnitude ranges. For instance, although our catalog of radial velocity members contains the largest number of stars spread over the largest range of colors, it also has a high probability of field star contamination due to the similarity of the kinematic distribution of the cluster compared to that of the field (Jeffries et al. 2009a). On the other hand, the catalog of stars showing X-ray emission has a much lower probability of contamination due to the ubiquitous nature of high magnetic activity in young stars compared to old field stars. However, the relatively low number of stars identified can be attributed to the fairly narrow field of view of the ROSAT X-ray satellite compared to the on-sky distribution of apparent cluster members. In an attempt to account for the relative power of using multiple membership criteria, Jeffries et al. (2009a) produced a catalog of highly probable members of IC 4665 using a combination of kinematic motions, lithium content, optical and 2MASS photometry, and spectral-index indicators as filters to remove foreground and background field star interlopers in the cluster catalog. We include this list of high-fidelity cluster members in our analysis and note that it is most current, up-to-date compilation of bona fide IC 4665 members.

In an effort to find an initial estimate for the age of IC 4665 using its low-mass population, we plot in Figure 6 the $V$ versus $V - I_c$ CMD for confirmed members of three open clusters; for IC 4665, the membership catalog from Jeffries et al. (2009a) is used, whereas the 35 Myr old NGC 2547 cluster, we employ the photometric membership catalog from Naylor et al. (2002).
The classic approach in determining fundamental properties of a young open cluster, such as age and distance, is finding a best-fitting CMD isochrone for the apparent cluster sequence. Typically, this is performed using a “by-eye” comparison of the model isochrone to the observational data, which can be burdened by uncertainties due to field star contamination and/or photometric error, as well as an apparent spread in the cluster sequence due to binarity. In this paper, we describe a new, statistical approach in modeling the lower-main-sequence of IC 4665.

3.1.1. \( \tau^2 \) Isochrone Modeling

The Tau-squared (\( \tau^2 \)) maximum likelihood statistic has recently been developed for modeling CMDs with two-dimensional theoretical isochrones (Naylor & Jeffries 2006; Naylor 2009). Examples of its application can be found in Jeffries et al. (2007, 2009b), Joshi et al. (2008), and Mayne & Naylor (2008). In short, \( \tau^2 \) is a generalized \( \chi^2 \) statistic that takes into account correlated uncertainties in two dimensions. Thus, we can use this statistical tool to effectively model a two-dimensional distribution, in our case an age- and distance-dependent CMD isochrone, to the \( V/B - V \) and \( V/Vc - Ic \) CMDs by minimizing \( \tau^2 \) to find a best-fitting isochrone.

Closely following the technique described in Naylor & Jeffries (2006) and Naylor (2009), we produce a grid of stellar model isochrones spanning a range of ages and distances. We
use the low-mass, solar-metallicity stellar evolution models from D’Antona & Mazzitelli (1997), Baraffe et al. (1998), and Siess et al. (2000), and employ a Pleiades tuning method to translate model luminosities and effective temperatures ($T_{\text{eff}}$) into magnitudes and colors (for a full description of the Pleiades tuning method, see Jeffries et al. 2001; Naylor et al. 2002). The $\tau^{2}$ software uses Monte Carlo methods to produce a probability, based on $\tau^{2}$, of finding a star drawn from the full photometric catalog (including photometric binaries) represented by each age–distance pixel on the grid. These probabilities are calculated for all stars in the CMD, and summed to derive the overall probability of the isochrone model being the best-fit isochrone for the modeled CMD.

In order to have our best-fit isochrones not be influenced by obvious outliers, we added an additional soft-clipping rejection step (Naylor & Jeffries 2006), whereby points having colors/magnitudes lying several $\sigma$ away from the range of model isochrones are ab initio removed from the modeling process. In our modeling of IC 4665, we assume an extinction relation of $A_v = 3.12 \times E(B-V)$, a reddening of $E(B-V) = 0.174$ (WEBDA Open Cluster Database), an $E(V-I_c) = 1.25 \times E(B-V)$ relation, and a binary fraction of 0.5 (Crampton et al. 1976).

We have assumed in our analysis that differential reddening is negligible for IC 4665. This is based on the results of Crawford & Barnes (1972) study finding the reddening in $B-V$ varied by only $\sim 0.02$ mag for 17 high-mass (B spectral-type) stars across the cluster. This amount of variation in $B-V$ color excess is at the level of our photometric internal precision ($\Delta(B-V) \sim 0.017$–0.022 mag) as determined by our nightly comparison analysis (see Section 2.2 and Table 4).

Once a best-fit isochrone for each of our IC 4665 CMDs is found, we derive the probability of the isochrone model being a good fit based on their minimum $\tau^{2}$ values. We include an additional magnitude-independent systematic uncertainty to the colors and magnitudes in our CMDs to increase their probabilities to an acceptable value (i.e., $\gtrsim 30\%$). This is analogous to the traditional method of increasing errorbars to arrive at a $\chi^{2}$ of 1 and ensures that the uncertainties on our ages and distances are appropriate relative to the scatter in the IC 4665 CMDs. Typically, we found that an additional $\sim 0.01$–0.03 increase is required for our $V, B,$ and $I_c$ magnitudes to achieve sufficiently high best-fit probabilities. This magnitude of systematic uncertainty can be easily explained by systematics in the standardization procedure (Naylor et al. 2002) or natural variability in such young, solar-type stars (e.g., spotted stars in IC 4665 have reported optical variability amplitudes of $\sim 0.03$–0.1 mag; Allain et al. 1996).

As an example of the basic procedure behind $\tau^{2}$ isochrone modeling, we plot in Figure 7 the $\tau^{2}$ grid derived from $V - I_c$ CMD isochrone modeling of the Jeffries et al. (2009a) membership catalog using the PMS models from D’Antona & Mazzitelli (1997). The displayed color scale indicates the total $\tau^{2}$ values for the indicated distance modulus (hereafter DM) and age grid points. The minimum value in this grid defines the best-fit age and DM for this membership catalog. This grid of $\tau^{2}$ values can also be thought of as a grid of probabilities (see above); therefore, $\tau^{2}$ values can be found for different confidence levels, e.g., displayed in Figure 7 is the 68% confidence contour. The ranges of ages and distances falling within this contour define the uncertainty in our best-fit measurements. We present in Figure 8 the best-fit isochrone from this $\tau^{2}$ grid analysis.

### 3.1.2. Pre-main-sequence Isochrone Results

In Figure 9, we show the best-fit ages and distances, derived from our Tau-squared fitting procedure, for each of our seven

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6 The $\tau^{2}$ software is publicly distributed by T. Naylor at [http://www.astro.ex.ac.uk/people/timn/tau-squared](http://www.astro.ex.ac.uk/people/timn/tau-squared).
IC 4665 membership catalogs (five individual catalogs described previously, the catalog from Jeffries et al. (2009a), and a combined catalog that includes any object with some type of membership criterion), and three stellar evolution models representing two different colors ($B-V$ and $V-I_c$). We note that we were unable to find a best-fit age and DM solution for every membership catalog using each model and/or color, with the rotation period and $H\alpha$ catalogs being particularly problematic. The failure of these model convergence is primarily due to the specifics of each membership catalog (e.g., large amounts of field-star contamination, not having a wide color–magnitude range in data points, etc.).

In the following analysis, we choose to use the membership catalog from Jeffries et al. (2009a) as the exemplar best-fit age and DM for the different models and colors, as it has the lowest probability of contamination by field stars (see Section 3.1). Nevertheless, modeling multiple membership catalogs allows us to identify the possible range of ages and DM one should expect when using specific membership criteria to identify cluster members. In Table 5, we list the median of the ages and distances, derived for all membership criterion catalogs, together with the observed range of values from our best-fit isochrone for each color and the stellar model. We also include the best-fit solution for the Jeffries et al. membership list.

For the most part, the best-fit ages and DM found for all three PMS models are typically within their individual errors of each other, suggesting that statistically they all three are in agreement with IC 4665’s age and distance. However, we do...
find that some points lie beyond 1σ from the other derived ages and DM (e.g., the best-fit parameters found for the V − Ic Li catalog using the D’Antona & Mazzitelli 1997 models) and are most likely the result of a poor fit due to limited or discrepant data. This is evidence for the strength of modeling multiple membership catalogs that we are able to clearly adjudicate whether an individual catalog’s measured age and DM is discrepant due to a poor isochrone fit or otherwise.

Here, we would like to highlight some results of our PMS isochrone modeling of IC 4665. First, if we focus solely on the B − V isochrones, we find good agreement in the measured DM for all three models, whereas only the ages for the D’Antona & Mazzitelli (1997) and Siess et al. (2000) models are in agreement with the best-fit values for Baraffe et al. model isochrones yielding systematically older ages (although they are within 1σ of the other authors’ models). For V − Ic, the derived ages for the three models are in close agreement, however, the Baraffe et al. models again yield slightly older ages. Furthermore, Baraffe et al. (2002) and Siess et al. (2000) models yield derived DM that are larger than the D’Antona & Mazzitelli (1997) V − Ic models.

Our results also show that all three models give systematically older ages for the B − V CMDs compared to the V − Ic ones. The color-dependent age discrepancies seen are of order ∼10 Myr, and are on the same order of offsets seen in other young open clusters when comparing isochrone fits using two different colors (see Naylor et al. 2002). We also note that for the Baraffe et al. (2002) and Siess et al. (2000) models, there is a color-dependent offset of ∼0.2 mag seen in the measured DM from the V − Ic CMDs. We find that the D’Antona & Mazzitelli (1997) models provide the most consistent age and DM between the IC 4665 B − V and V − Ic CMDs.

At this point, we caution the reader that the observed model- and color-dependent discrepancies in ages and DM are likely due to many different influences and may not necessarily be representative of problems with low-mass stellar evolution models. Indeed, these three models include different physics that almost certainly must lead to different predicted luminosities and effective temperatures at given ages (for detailed discussion, see Siess et al. 2000; Hillenbrand & White 2004); however, the observed offsets may also be the result of systematics in the modeling process. For example, the ages derived from the B − V CMDs may be older due to the B − V color of late-type stars becoming nearly insensitive to changes in effective temperature, which consequentially makes it difficult to assign a PMS isochrone to such low-mass stars. In addition, the Pleiades tuning method may also introduce systematic errors into our analysis. For instance, Stauffer et al. (2007) find that low-mass stellar evolution models have trouble fitting the observed optical and infrared colors of low-mass members of the Pleiades. Because we calibrate our IC 4665 colors and magnitudes using an empirical fit to the Pleiades main sequence, any such systematics in the Pleiades tuning method are included in our isochrone modeling procedure. More generally, however, by employing the Pleiades tuning method we are assuming that the colors and magnitudes of the Pleiades main-sequence stars are representative of the younger stars in IC 4665. Unfortunately, our IC 4665 dataset is relatively small compared to other well-studied open clusters and does not include a complete, contaminant-free PMS, which therefore may not allow us to disentangle all of the different color- and model-dependent systematics affecting PMS isochrones modeling.

Keeping this in mind, we would nevertheless still like to derive a single, best-fit PMS age and distance for IC 4665 for comparison purposes. Since the Jeffries et al. catalog is most likely to contain the highest number of bona fide IC 4665 members, we use this catalog’s resulting best-fit isochrone ages and DM as representative of the cluster. First, we calculate the inter-model error-weighted mean age and DM for the B − V and V − Ic colors, separately. The errors on these values are asymmetric; therefore, the weights for our means are based on whether the age/DM lies above or below the straight average, e.g., if an age lies below the straight average, we then weight that data point using its upper error value. Using this approach, we find color-dependent ages of 30.6 ± 3.5 and 49.3 ± 9.0 Myr, as well as intrinsic DM of 7.88 ± 0.05 and 7.75 ± 0.03 mag (377 ± 9 and 355 ± 3 pc), for our B − V and V − Ic CMDs, respectively. Taking the weighted mean of these color-dependent values, we get a final PMS age and DM for IC 4665 of 35.8 ± 9.3 Myr and 7.78 ± 0.07 mag (360 ± 12 pc), for which the quoted errors are uncertainties in the mean.

The entire photometric catalog of IC 4665 fields is plotted in Figure 10 in the form of V/ V − Ic and V/ B − V CMDs, where stars having photometric data consistent (within the errors) of being photometric members of 36 Myr and 360 pc D’Antona & Mazzitelli (1997) isochrones are highlighted. For each of these candidate photometric members of IC 4665, we list their astrometric and photometric properties in Table 6. This photometric membership selection is based upon D’Antona & Mazzitelli because our model- and color-averaged age and DM are most closely matched to the values we get from the individual modeling of the V − Ic and B − V CMDs compared to the other theoretical PMS models generated by other authors (e.g., Baraffe et al. 2002; Siess et al. 2000). Although this membership list most likely contains a high number of cluster members, its exclusive use in identifying members of IC 4665 is not recommended due to the non-zero probability of field star contamination in the catalog, especially where the Galactic field star distribution intercepts the cluster main-sequence close to (V − Ic)0 ∼ 1.00 and (B − V)0 ∼ 1.25.
Previously, we have shown that the CMDs of IC 4665 members appear very similar to those of the ∼35 Myr old NGC 2547 cluster (see Figure 6), which is now empirically supported by our PMS age determination for IC 4665. Moreover, the best-fit DM that we derive for the cluster is in excellent agreement with the trigonometric parallax distance resulting from the recent re-reduction of the HIPPARCOS astrometric dataset by van Leeuwen (2009), which yields an intrinsic DM of 7.75 ± 0.21 mag (355 ± 35 pc). Following Naylor (2009), we use upper-main-sequence models from Lejeune & Schaerer (2001), and within the error budget, are in agreement with the trigonometric parallax distance resulting from the recent re-reduction of the HIPPARCOS astrometric dataset by van Leeuwen (2009), which yields an intrinsic DM of 7.75 ± 0.21 mag (355 ± 35 pc).

### 3.2. Upper-main-sequence Turn-off Age

Comparing the positions of open cluster upper-main-sequences in color–magnitude space, Mermilliod (1981a) determines that IC 4665 had a nuclear turn-off age of 36 Myr. However, P93 suggest that the upper-main-sequence for IC 4665 is best comparable to that of the ∼70 Myr open cluster α Persei, and if effects due to rapid rotation are taken into account, the upper-main-sequence is most like the Pleiades CMD, suggestive of a cluster age near to ∼100 Myr.

In light of this disagreement in nuclear turn-off age for IC 4665, we now use the τ‡ technique, outlined in Section 3.1, to measure an age and distance for only the high-mass cluster members. Because the main-sequence turn-off for IC 4665 is located at a V magnitude brighter than our CTIO photometric survey saturation limit, we utilize the bright (V < 11 mag) optical data from P93 and Menzies & Marang (1996). Unfortunately, neither catalog contained published individual uncertainties on their photometric data; therefore, we set the error in the B and V magnitudes to the level of observed scatter in P93 data in stars with V < 14 mag found in our catalog comparison (ΔV = 0.07 mag and ΔB − V = 0.1 mag, see Section 2.3). Following Naylor (2009), we use upper-main-sequence models from Lejeune & Schaerer (2001) and Girardi et al. (2002), coupled with solar-metallicity bolometric corrections and effective temperature to color conversions, as well as color-dependent reddening vectors from Bessell et al. (1998).

We find upper-main-sequence ages for IC 4665 of 41 ± 12 and 42 ± 12 Myr and intrinsic DM of 7.76 ± 0.04 and 7.77 ± 0.04 mag (356 ± 10 and 358 ± 15 pc) for the aforementioned different high-mass stellar evolution models, respectively. We plot in Figure 11 the photometric data used in our high-mass CMD modeling as well as our two best-fit isochrones. We note that this age measurement is not thoroughly constrained due to the lack of high-mass cluster members tracing out IC 4665’s upper-main-sequence; nevertheless, we find that the nuclear turn-off age for IC 4665 we have calculated is similar to the previous estimate from Mermilliod (1981a), and within the error budget, are in agree-

### Table 6

Catalog of IC 4665 Photometric Members

| Mosaic Number | V      | B−V   | V − Ic | Phot Mem\textsuperscript{a} | Phot Mem\textsuperscript{b} | Mem Key\textsuperscript{b} |
|---------------|--------|-------|-------|-----------------------------|-----------------------------|-----------------------------|
| F1            | 427    | 13.069 ± 0.002 | 0.816 ± 0.005 | 0.997 ± 0.004 | Y | Y | Li,RV,J, |
| F6            | 347    | 12.729 ± 0.002 | 0.835 ± 0.004 | 1.018 ± 0.003 | N | Y | Li,XR,RP |
| F6            | 59     | 14.475 ± 0.006 | 1.252 ± 0.019 | 1.274 ± 0.009 | Y | Y | RV |
| F6            | 338    | 12.095 ± 0.001 | 0.628 ± 0.002 | 0.754 ± 0.002 | Y | Y | ... |

Notes.

\textsuperscript{a} Point lies within its photometric uncertainty of the isochrone using the specified color.

\textsuperscript{b} Ancillary membership criterion. See Section 3.1 for source references. Li, lithium absorption; XR, X-ray emission; H, H\alpha emission; RV, radial velocity; RP, detected rapid rotation period; J, listed as member in Jeffries et al. (2009a); and “...”, photometric member only.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal.)

A portion is shown here for guidance regarding its form and content.)

![Figure 10: Intrinsic V − Ic and B−V CMDs for IC 4665 are plotted for our entire photometric catalog. Stellar objects having colors and magnitudes consistent, within their photometric errors, of a 36 Myr and 360 pc D’Antona & Mazzitelli (1997) model isochrone (red solid line) are highlighted (blue diamonds), together with the locus of its associated equal-mass binary sequence (red dotted line). Photometric data have been dereddened using an $A_V = 0.543$, an $E(B − V) = 0.174$, and an $E(V − I_c) = 0.2175$.](image-url)
ment with the $\alpha$ Persei-like age estimate from P93 (although quite discrepant from P93’s Pleiades-like age estimate).

Naylor (2009) recently investigated the differences observed in isochronal ages measured from upper- and lower-main-sequence of young ($<100$ Myr) open clusters. They find a trend of PMS turn-on ages being ~1.5 times smaller than nuclear turn-off ages for a selection of young open clusters. Interestingly, our current study on IC 4665 shows that the upper-main-sequence isochrone models have best-fit ages that are similar (difference of ~6 Myr) to the PMS isochrone age while using the $B-V$ low-mass CMD. However, if we use the PMS isochrone age from the $V-I$, CMDs ($30.6 \pm 3.5$ Myr) or our inter-model $V-I$, mean PMS age ($35.8 \pm 9$ Myr), we find ~1.5 times these PMS ages are formally within uncertainty of the nuclear turn-off age (i.e., $1.5 \times 30.6 \pm 3.5$ Myr = $45.9 \pm 3.5$ Myr and $1.5 \times 35.8 \pm 9$ Myr = $53.7 \pm 9$ Myr, compared to our turn-off age of $42 \pm 12$ Myr), corroborating the Naylor (2009) findings.

### 3.3. Lithium Depletion Boundary Age

Using the LDB to date young open clusters provides a precise (~10% uncertainty), nearly model-insensitive method to determine ages for open clusters (Burke et al. 2004; Jeffries & Oliveira 2005). It has been found that LDB ages for open clusters tend to be systematically older than upper-main-sequence turn-off ages (Stauffer et al. 1998, 1999; Barrado y Navascués et al. 2004; Burke et al. 2004); however, the discrepancy between LDB and turn-off ages has been found to be smaller for younger open clusters (Jeffries & Oliveira 2005; Naylor 2009) and may not exist for PMS isochrone ages (Jeffries & Oliveira 2005).

IC 4665 provides an interesting test for these age discrepancies in young open clusters because it is one of the few clusters with an LDB age in addition to well-defined PMS and upper-main-sequence populations. We recall that Manzi et al. (2008) measured an LDB age of $28 \pm 5$ Myr for IC 4665, which is in agreement within the error budget, with our $35.8 \pm 9.3$ Myr model-averaged PMS age determination. We also find the upper-main-sequence age for IC 4665 ($42 \pm 12$ Myr) is 1.5 times older than the LDB age, thereby contradicting the trend seen in other open clusters with LDB ages. We note, however, that the paucity of high-mass stars in PMS open clusters like IC 4665 reduces the fidelity of their turn-off ages; therefore, this discrepancy in the observed turn-off-LDB age trend may turn out to be of little significance.

### 3.4. X-ray Activity and Age

There is a very distinct, age- and mass-dependent morphology of X-ray activity observed in young open clusters that is fundamentally tied to the causal relationship between age-dependent stellar rotation and the presence of a rotationally induced, magneto-hydrodynamic dynamo in young stars (for review, see Güdel 2004). More specifically, the distribution of X-ray emission, typically expressed as the distance-independent ratio of X-ray to bolometric luminosity ($L_x/L_{bol}$), can be described by two regimes: first, a regime where $L_x/L_{bol}$ more or less monotonically increases with decreasing stellar mass (and independently, with decreasing stellar period); and second, the so-called saturated regime, where there is a plateau in X-ray emission at $L_x/L_{bol} \sim 10^{-3}$ regardless of changes in stellar mass or change in stellar rotation rate (Hemppelmann et al. 1995; James et al. 2000). The physical cause of this saturated regime is still a matter of debate (Charbonneau & MacGregor 1992; O’dell et al. 1995; Jardine & Unruh 1999); however, the transition point between these two regimes is empirically found to be a function of rotation period for a given stellar mass (Pizzolato et al. 2003), and therefore, a function of age due to the time dependence of stellar rotation (Barnes 2003, 2007; Mamajek & Hillenbrand 2008). For example, in a young cluster like NGC 2547 (~35 Myr), even the higher mass stars (~G-type stars) are rotating significantly fast enough to be in the saturated X-ray regime (Jeffries et al. 2000), while in an older cluster like the Hyades (~700 Myr) the transition point between the two regimes is found in the M dwarfs mass domain (Stern et al. 1995). Consequently, we can assign approximate ages of open clusters, in a relative manner, by comparing their X-ray distributions to those of clusters with known ages, and comparing the observed color (i.e., stellar mass) at which there is a transition from the linearly increasing, color-dependent X-ray luminosity function to the saturated regime.

In the ROSAT study of IC 4665 (Giampaoli et al. 1998), the authors suggest that IC 4665 has an X-ray distribution indicative of a cluster which is older than the $\alpha$ Persei (~70 Myr), and very similar to the Pleiades (~120 Myr). They find that the color at which the IC 4665 X-ray distribution appears to transition to the saturated regime is redder (lower-mass) than $\alpha$ Persei and is in agreement with the color of saturation for the Pleiades. Therefore, according to the age–activity relationship, IC 4665 should have an age of ~120 Myr. This finding is formerly discordant with our current high- and low-mass isochronal analysis of IC 4665 (Sections 3.1 and 3.2), as well as its measured LDB age.

In order to evaluate the validity of this X-ray age determination, we utilize our new optical photometry and several X-ray surveys of other clusters published since the Giampapa et al. (1998) study, including several with data from the new generation of X-ray telescopes (Chandra and XMM-Newton X-ray observatories). For ROSAT X-ray detected stars in IC 4665, we assign new colors ($V-I$) and calculate new bolometric luminosities.
to be in disagreement with the overall observed activity-age morphology. We note that Cargile et al. (2009) similarly find the Pleiades X-ray distribution is at odds with the approximately coeval open cluster Blanco 1, and speculate that this discrepancy is primarily due to scatter in the Pleiades photometric data, and is not attributable to the stellar properties of Blanco 1 members.

3.5. Hα Emission and Age

Much like X-ray activity, studies of chromospheric activity have also been used as a good indicator of relative age for open clusters (Prosser et al. 1991; Stauffer et al. 1991; Prosser 1992). Through its causal relationship to the solar-type dynamo, the level of chromospheric emission changes as a function of stellar rotation, and therefore ultimately on age (Mamajek & Hillenbrand 2008). More specifically, as a star spins down with age, reduced emission is observed in chromospheric lines, e.g., Hα, Ca II H & K (Wilson 1963).

Similar to the X-ray study of Giampapa et al., P93 claim that IC 4665 has an age of ≥100 Myr based on the upper envelope of its Hα EW distribution, as a function of pseudo-MK (pMK) spectral type, being below that seen for the Pleiades, thus in direct conflict with our current isochrone dating analysis and its measured LDB age. P93 derived pMK spectral types using a series of line ratios, mostly strong TiO features, measured from their low-dispersion spectra. Here, using our new photometric catalog and Hα data listed in Section 3.1, we reanalyze the Hα distribution in IC 4665 to investigate the reported chromospheric activity–age estimate of ~100 Myr. In Figure 13 (left panel), we plot Hα EW (EW_Ha) taken from P93 as a function of our new intrinsic V – Ic color. We also plot Hα data for open clusters NGC 2547 (35 Myr; Jeffries et al. 2000), IC 2391/IC 2602 (50 Myr; Stauffer et al. 1997), and Blanco 1 (100 Myr; Panagi & O’dell 1997, D. J. James et al. 2010, in preparation). The level of Hα emission seen, as well as the color at which Hα is observed in emission, in IC 4665 indicates that the cluster is younger than 50 Myr, and most likely has an age near (or younger) than that of NGC 2547 (35 Myr).

When we plot the Hα emission distribution of IC 4665 and the Pleiades (Stauffer & Hartmann 1987) using V – Ic, instead of using the pMK spectral-type classification schema, as a proxy for effective temperature (Figure 13, right panel), we see that the two clusters have dissimilar morphologies. The onset of Hα in emission in IC 4665 is found at an earlier spectral type compared to the Pleiades, thus suggesting that IC 4665 is younger than the ~120 Myr old Pleiades. This finding is contrary to the chromospheric dating analysis in P93; however, their Hα line measurements were performed over a much more limited range of spectral types with the earliest being ~M0. With our more extensive sample of Hα measurements from three different sources (Prosser 1993; Martin & Montes 1997; Jeffries et al. 2009a), we clearly observe Hα emission in IC 4665 stars as early as spectral type ~G0 ((V – Ic)0 ~ 0.7), thereby suggesting a much earlier age estimation.

4. SUMMARY AND CONCLUDING REMARKS

In this paper, we present the results of a new, homogeneous, standardized BVIc photometric survey of the central region of the young open cluster IC 4665. This dataset improves upon the previous work of P93, by incorporating a high-fidelity standardization procedure involving observations of multiple standards taken contemporaneously with our IC 4665 data. Our

![Figure 12. Ratio of X-ray to bolometric luminosity plotted as a function of intrinsic V – Ic color for X-ray sources taken from Giampapa et al. (1998) with counterparts in our optical catalog for IC 4665 (blue asterisks). In each relevant panel, also plotted are X-ray data for NGC 2547 (red squares), IC 2391/IC 2602 (orange diamonds), α Persei (purple triangles), Blanco 1 (black crosses), Pleiades (light blue triangles), and M 7 (green circles). Data are taken from Jeffries et al. (2000), Stauffer et al. (1997), Randich et al. (1996), Cargile et al. (2009), Stauffer et al. (1994), and Prosser et al. (1995), respectively. Spectral-type ranges, as defined by Bessell et al. (1998), are plotted along the top axes. Intrinsic colors were calculated using E(B – V) values collated in the WEBDA database and an E(V – Ic) = 1.25 × E(B – V) relation.](image-url)
in the results from the PMS isochrones. This large spread in ages and distances, as well as the systematic offsets seen between stellar parameters from the different sets of models. At this point, how these systematic model- and color-dependent offsets influence the measured ages and distances cannot be completely deciphered primarily due to a limited number of known clusters members and a relatively high non-member contamination level of IC 4665.

In addition, we also compared the distribution of magnetic activity in IC 4665 stars to other well-studied open clusters. The coronal X-ray and chromospheric Hα emission observed in IC 4665 is most similar to 30–40 Myr old clusters (e.g., NGC 2547), thereby providing further confirmation on our measured turn-on and turn-off ages. This result also provides further evidence against previous claims that IC 4665 has an observed activity distribution similar to the Pleiades. Previous IC 4665 activity–age studies have been reliant on relative distribution comparisons with clusters that we find do not fit into the observed global trends seen in larger samples of open clusters, particularly the X-ray emission distribution of α Persei and the Pleiades.

While it is clear that we do see slight offsets and differences in the various dating techniques we have employed in this paper, the majority of our measured ages for IC 4665 are consistently between ~30 and 45 Myr. Interestingly, the lack of large systematic differences (factors of > 1.5 in age) between dating techniques is not typical for open clusters; for example, published ages for the Pleiades range from 70 Myr (Mermilliod 1981b) to 150 Myr (Burke et al. 2004). Understanding why IC 4665 does not suffer from these systematic offsets should allow for a critical comparison between the different methods available to determine stellar ages.

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