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THE B AND Be STAR POPULATION OF NGC 3766

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ABSTRACT

We present multiple epochs of Hα spectroscopy for 47 members of the open cluster NGC 3766 to investigate the long-term variability of its Be stars. Sixteen of the stars in this sample are Be stars, including one new discovery. Of these, we observe an unprecedented 11 Be stars that undergo disk appearances and/or near disappearances in our Hα spectra, making this the most variable population of Be stars known to date. NGC 3766 is therefore an excellent location to study the formation mechanism of Be star disks. From blue optical spectra of 38 cluster members and existing Strömgren photometry of the cluster, we also measure rotational velocities, effective temperatures, and polar surface gravities to investigate the physical and evolutionary factors that may contribute to the Be phenomenon. Our analysis also provides improvements to the reddening and distance of NGC 3766, and we find $E(B-V) = 0.22 \pm 0.03$ and $(V - M_V)_0 = 11.6 \pm 0.2$, respectively. The Be stars are not associated with a particular stage of main-sequence evolution, but they are a population of rapidly rotating stars with a velocity distribution generally consistent with rotation at 70%–80% of the critical velocity, although systematic effects probably underestimate the true rotational velocities, so that the rotation is much closer to critical. Our measurements of the changing disk sizes are consistent with the idea that transitory, nonradial pulsations contribute to the formation of these highly variable disks.

Subject headings: open clusters and associations: individual (NGC 3766) — stars: emission-line, Be

1. INTRODUCTION

NGC 3766 is a rich, young open cluster in the Carina spiral arm that is well known for its high content of Be stars (Slettebak 1985), and many previous studies of this cluster have focused on the characteristics of these stars to identify their evolutionary status. The cluster has been the target of numerous photometric studies (Ahmed 1962; Yilmaz 1976; Shobbrook 1985, 1987; Moitinho et al. 1997; Piatti et al. 1998; Tadross 2001; McSwain & Gies 2005b). But despite these intensive investigations, the cluster's age and distance remain somewhat uncertain; measurements of its age range from 14.5 to 25 Myr (WEBDA;[5] Moitinho et al. 1997; Tadross 2001), and its distance is between 1.5 and 2.2 kpc. The reddening $E(B-V)$ is between 0.16 and 0.22 (see the discussion of Moitinho et al. 1997).

Spectroscopic investigations of NGC 3766 have targeted a limited sample of cluster members, focusing primarily on the Be star and supergiant populations (Harris 1976; Mermilliod 1982, and references therein; Slettebak 1985; Levesque et al. 2005). Even the eclipsing double-lined spectroscopic binary BF Centauri (=HD 100915), a member of NGC 3766, has been largely neglected by modern spectroscopic observations (Clausen et al. 2007 and references therein). For most cluster members, no detailed information about their physical characteristics such as temperature, gravity, rotation, and metallicity are known.

In this work we present red and blue optical spectra for both normal B-type and Be stars in the cluster. Like many prior studies of NGC 3766, our primary goal is to investigate the Be star population; but unlike other works, we achieve a more complete understanding of this subset of B stars by comparing these emission-line objects to their nonemission counterparts. Therefore, we present measurements of the effective temperature, $T_{\rm eff}$, surface gravity, $\log g$, and in most cases the projected rotational velocity, $V \sin i$, for 26 normal B stars and 16 Be stars in NGC 3766. We use these results to improve the known reddening and distance to the cluster. From multiple epochs of Hα spectroscopy, we also investigate the variability of the circumstellar disks and estimate the disk mass-loss/gain rates for 11 Be stars. Finally, we use the observed disk masses and angular momenta to show that nonradial pulsations are a possible origin of the disks, which probably fill during short-lived bursts of mass flow from the stellar surface.

2. OBSERVATIONS

We obtained spectra of NGC 3766 during multiple observing runs in 2003 March, 2005 February, 2006 May, and 2007

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[5] The WEBDA database is maintained by E. Paunzen and is available online at http://www.univie.ac.at/webda/navigation.html. See also Vizier Online Catalog, VII/92A (G. Lynga 1987).

TABLE 1
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UT Dates	Range (Å)	Resolving Power ($\lambda/\Delta\lambda$)	Number of Spectra	Telescope and Spectrograph	Slit Plate (μm)	Grating	Filter	Detector
2003 Mar 21–22	5490–6790	1800	20	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2005 Feb 2	4100–6900	1900	47	CTIO Blanco 4 m + Hydra	200	KPGL3/1	...	SITe 4K × 2K
2006 May 13	3790–4708	3170	38	CTIO Blanco 4 m + Hydra	...	KPGLD/2	BG39	SITe 4K × 2K
2006 May 14–15	5125–8000	1560	47	CTIO Blanco 4 m + Hydra	...	KPGL3/1	...	SITe 4K × 2K
2007 May 4–5	5125–8000	2000	45	CTIO Blanco 4 m + Hydra	200	KPGL3/1	...	SITe 4K × 2K
2007 Jan 20	5650–6790	1700	10	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Jan 29	5650–6790	1700	2	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Feb 2	5650–6790	1700	8	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Apr 26	5650–6790	1700	5	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Jun 9	5650–6790	1700	1	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Jun 30	5650–6790	1700	9	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Jul 3	5650–6790	1700	2	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K
2007 Jul 27–28	5650–6790	1700	7	CTIO 1.5 m + Cassegrain	...	47/1	GG495	Loral 1K × 1K

January–July using the CTIO Blanco 4 m telescope with the Hydra multifiber spectrograph and the CTIO 1.5 m telescope with the Cassegrain spectrograph, operated by the SMARTS Consortium. The details of all runs are summarized in Table 1. Most of the runs targeted the Hα emission-line profile with low spectral resolution to characterize the Be stars' emission; however, during one run we observed the blue optical region with higher resolving power to observe numerous other H Balmer and He I line profiles and measure the physical parameters of the cluster members.

We selected the targets for each run by giving highest priority to the known Be stars in this cluster (save WEBDA star 232, which was saturated in our photometric study). We then selected other B-type stars in the cluster by ranking them according to their $y -$ Hα color to preferentially select any weak emission stars that were not detected in our photometry (McSwain & Gies 2005a, 2005b). All observations were performed by M. V. M. except the 2007 CTIO 1.5 m runs, which were taken in service mode by a SMARTS observer. For the Hydra observations, we generally began by taking short exposures and then parking the fibers used for the brightest stars to avoid saturation in the longer exposures. Not all of the known Be stars could be observed in one fiber configuration, so we took three to four exposures each of two configurations to observe all of the targets. Therefore, up to eight exposures of each star were obtained with the Hydra runs. We also observed a HeNeAr comparison lamp source just before and after the set of cluster observations for wavelength calibrations. For the CTIO 1.5 m observations, we alternated each stellar observation with a Ne comparison lamp spectrum.

The CTIO 1.5 m spectra were reduced and rectified to a unit continuum using standard routines for slit spectra in IRAF.[6] All of the Hydra spectra were zero-corrected using standard routines in IRAF, and they were flat-fielded, wavelength-calibrated, and sky-subtracted in IRAF using the `dohydra` routine. In comparing the slit spectra and fiber spectra for many of the same objects in our data set, we find no evidence of systematic differences in the background subtraction due to cluster nebulosity. For each Hydra spectral configuration, we transformed the observations to a common heliocentric wavelength grid and co-added them to achieve a good signal-to-noise ratio for each star.

The complete sample of stars presented in this work is listed in Table 2. Column (1) gives each star's identification number based on the assigned number in McSwain & Gies (2005b); the corresponding WEBDA numbers are given in column (2), where available. We obtained Hα spectra for each of these stars during at least three epochs in most cases, and these are shown in Figures 1*a*–1*c*.

3. PHYSICAL PARAMETERS FROM SPECTRAL MODELS

3.1. *V* sin *i* Measurements

We began our investigation of each star's physical parameters by generating a grid of synthetic, plane-parallel, local thermodynamic equilibrium (LTE) atmospheric models using the Kurucz ATLAS9 code (Kurucz 1994). We adopted solar abundances and a microturbulent velocity of 2 km s^{-1} for these stars, which corresponds to the mean microturbulence observed among late-type, main-sequence (MS) B stars (Lyubimkov et al. 2004). Each atmospheric model was then used to calculate a grid of model spectra using SYNSPEC (Lanz & Hubeny 2003).

For the 38 stars with available blue spectra, we made a preliminary estimate of their effective temperature and gravity, $T_{\rm eff}$ and log g, respectively, by comparing the observed Hγ, Hδ, He I λ4143, and He I λ4471+Mg II λ4481 line profiles to our grid of Kurucz spectral models. To measure V sin i, we compared the observed He I line profiles to the model profiles convolved with a limb-darkened, rotational broadening function and a Gaussian instrumental broadening function. We determined the best fit over a grid of values, spaced 2 km s^{-1} apart, minimizing the mean square of the deviations, rms^2. The formal error, ΔV sin i, is the offset from the best-fit value that increases the rms^2 by 2.7rms$^2/N$, where N is the number of wavelength points within the fit region. Our measured V sin i and ΔV sin i are listed in columns (3)–(4) of Table 3.

Even the He I lines may contain some weak emission in Be stars, partially filling and narrowing their line profiles. Furthermore, a number of the Be stars show evidence of narrow "shell" line components (formed in the outer disk), and the presence of a shell component may make the profile appear too narrow in some cases. Therefore, we consider our V sin i measurements for the Be stars to be lower limits. However, we note that the He I lines do not exhibit obvious signs of emission among most of the Be stars, and these lines are much less susceptible to emission than the Hγ or Hδ lines. For the case of star 154, a shell star with strong emission and contamination present in the He I lines, we used the Mg II λ4481 line to measure V sin i.

There are few previous measurements in the literature of V sin i for members of NGC 3766, but we found that 10 stars in

[6] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under cooperative agreement with the NSF.

TABLE 2

Hα Equivalent Widths

MG ID	WEBDA ID (1)	W_λ (Å) (2003 Mar) (2)	W_λ (Å) (2005 Feb) (3)	W_λ (Å) (2006 May) (4)	W_λ (Å) (2007 Jan/Feb) (5)	W_λ (Å) (2007 Apr) (6)	W_λ (Å) (2007 May) (7)	W_λ (Å) (2007 June) (8)	W_λ (Å) (2007 July) (9)
2	...	...	3.24	4.07	...	...	3.93	...	...
16	169	...	4.28	4.26	...	...	3.84	...	...
23	...	...	9.22	9.37	...	...	7.59	...	...
25	291	3.62	3.18	5.30	−1.63, −1.06	0.42	1.04	1.42	...
27	146	5.14	5.38	5.69	...	...	4.74	...	...
31	151	2.91	3.99	0.57	−3.34, −5.94	−6.64	−6.80	...	...
36	13	...	8.46	8.56	...	...	6.93	...	...
41	130	...	4.88	5.28	...	...	4.41	...	...
42	178	...	6.07	6.02	...	...	5.22	...	...
45	8	4.69	4.98	5.10	...	...	4.35	...	...
47	15	−14.99	−11.33	−11.29	−8.11	...	−6.81	−5.61	−4.68
49	137	4.87	4.37	4.89	...	...	4.25	...	...
54	125	...	5.18	5.61	...	...	4.84	...	...
55	...	...	5.03	5.12	...	...	4.59	...	...
57	24	...	5.67	5.86	...	...	4.72	...	...
61	20	...	4.09	3.54	3.66	...	3.56	4.41	1.20
69	...	...	2.89	3.19	...	...	2.81	...	...
72	4	7.19	8.27	8.65	7.14	...	7.08	...	7.25
73	26	3.65	0.42	3.28	1.27	...	−0.35	...	−0.92
77	195	4.85	4.61	5.72	...	...	4.73	...	...
83	27	0.53	4.07	0.84	2.92	3.72	2.93	...	...
92	1	2.06	2.31	2.73	3.32	...	3.41	2.66	...
94	194	...	5.94	5.91	...	...	4.94	...	...
96	45	...	6.39	6.87	...	...	6.26	...	...
98	36	4.99	3.10	0.21	4.43	4.36	4.14	...	5.05
101	34	...	7.40	7.44	...	...	...	...	...
118	...	...	7.40	7.03	...	...	5.73	...	...
119	81	4.76	−5.48	−3.19	−6.53	...	−8.67	...	−12.83
126	...	...	7.46	8.49	...	...	6.86	...	...
127	53	−7.21	−4.95	−4.00	−4.19	...	−5.47	−5.60	−12.81
129	...	...	8.66	7.94	...	...	6.84	...	...
130	67	...	2.00	5.04	4.23	...	4.44	4.38	...
133	63	4.40	−1.15	−9.14	−11.62	...	−12.72	−12.40	...
139	204	8.48	5.46	4.24	4.51	4.50	4.42	5.54	...
154	88	−33.46	−40.07	−33.56	−34.37	...	−33.95	...	−36.16
155	...	...	7.92	7.90	...	...	6.38	...	...
161	70	...	3.92	4.19	...	...	3.61	...	...
162	...	...	9.15	9.23	...	...	7.45	...	...
170	94	...	4.81	5.26	...	...	4.17	...	...
173	233	...	7.79	7.92	...	...	6.62	...	...
175	218	...	6.67	6.74	...	...	6.01	...	...
178	213	...	6.32	7.71	...	...	6.35	...	...
190	260	...	6.81	6.86	...	...	...	...	...
196	239	4.52	4.32	4.39	...	...	1.46	...	...
197	253	...	7.65	8.85	7.04	...	7.09	...	7.66
198	264	−39.49	−43.40	−53.71	−52.77	...	−53.44	−54.69	...
200	240	−8.84	−6.66	−4.62	−4.88	...	−5.19	−5.76	...

our sample were also measured by Slettebak (1985). Our $V \sin i$ measurements generally agree well, with the exception of star 154. Slettebak found $V \sin i = 220$ km s^{-1} for that star, nearly double our measured value. We emphasize that the exceptionally strong He and metal lines of this shell star amplify the difficulty of measuring its $V \sin i$.

3.2. $T_{\rm eff}$ *and* log g *Measurements of* B *stars*

For the B stars with $T_{\rm eff} < 15{,}000$ K, we used the "virtual-star" method of Huang & Gies (2006) to improve our $T_{\rm eff}$ and log g measurements. (Their virtual star is a spherically symmetric star with constant $T_{\rm eff}$ and log g across the stellar surface.) They generated detailed Hγ line profiles using line-blanketed, LTE Kurucz ATLAS9 and SYNSPEC codes. Huang & Gies show that the Hγ line strength and equivalent width can be used as starting parameters in a line profile fit to obtain unique values of $T_{\rm eff}$, log g, and their corresponding errors. We used their procedure to measure these quantities from our observed Hγ line profiles.

Among the hotter B-type stars, non-LTE effects alter the equivalent width of the Hγ line, and thus the LTE Kurucz model line profiles systematically underestimate $T_{\rm eff}$. Therefore, we used the new TLUSTY BSTAR2006 grid of metal line-blanketed, non-LTE, plane-parallel, hydrostatic model spectra (Lanz & Hubeny 2007) to measure $T_{\rm eff}$ and log g for those stars with $T_{\rm eff} > 15{,}000$ K. We used their models with solar metallicity and helium abundance and a microturbulent velocity of 2 km s^{-1}. The grid includes $T_{\rm eff}$ from

study of several other clusters from our survey, and we will address those results in a future paper.

While the Be stars of NGC 3766 are not distinguishable from normal B-type stars by their evolutionary states, they do form a population of rapidly rotating stars. With two exceptions, their measured velocities are consistent with a uniform population of rapid rotators having $V = 0.7$–$0.8V_{crit}$. Gravitational darkening and weak emission in the He I lines may mean that these velocities are underestimated by as much as 33% (Townsend et al. 2004), so the true V_{rot} is probably at least $0.84V_{crit}$. From the measured changes in the disks' masses and angular momenta, NRPs are adequate as a source for the mass flow into the equatorial plane. The pulsations may be a transitory phenomenon, however, and the variable nature of the Be stars probably reflects dramatic changes in the surface activity.

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Facilities: CTIO:1.5m, CTIO:4m

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