THE ROLE OF EVOLUTIONARY AGE AND METALLICITY IN THE FORMATION OF CLASSICAL Be CIRCUMSTELLAR DISKS. II. ASSESSING THE EVOLUTIONARY NATURE OF CANDIDATE DISK SYSTEMS

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ABSTRACT

We present the first detailed imaging polarization observations of six SMC and six LMC clusters, known to have large populations of B-type stars that exhibit excess H$\alpha$ emission from 2-CD photometric studies, to constrain the evolutionary status of these stars and hence better establish links between the onset of disk formation in classical Be stars and cluster age and/or metallicity. We parameterize and remove the interstellar polarization (ISP) associated with each line of sight, thereby isolating the presence of any intrinsic polarization. We use the wavelength dependence of this intrinsic polarization to discriminate pure gas disk systems, i.e., classical Be stars, from composite gas-plus-dust disk systems, i.e., Herbig Ae/Be or B[e] stars. Our intrinsic polarization results, along with available near-IR color information, support the suggestion of Wisniewski et al. that classical Be stars are present in clusters of age 5–8 Myr and contradict assertions that the Be phenomenon only develops in the second half of a B star’s main-sequence lifetime, i.e., no earlier than 10 Myr. The prevalence of polarimetric Balmer jump signatures decreases with metallicity; we speculate that either it is more difficult to form large disk systems in low-metallicity environments or that average disk temperatures are higher in low-metallicity environments. The polarimetric signatures of $\sim$25% of our sample appear unlikely to arise from true classical Be star disk systems, suggesting one should proceed with caution when attempting to determine the role of evolutionary age and/or metallicity in the Be phenomenon purely via 2-CD results.

Subject headings: circumstellar matter — galaxies: clusters: individual (Bruck 60, NGC 330, NGC 346, NGC 371, NGC 456, NGC 458, LH 72, NGC 1818, NGC 1858, NGC 1948, NGC 2004, NGC 2100) — Magellanic Clouds — stars: emission-line, Be — techniques: polarimetric — stars: individual (π Aquarii, BD +61 154, MWC 349A)

Online material: machine-readable tables

1. INTRODUCTION

While the rapid rotation ($v_{rot}/v_{crit} \approx 70\%–80\%$ of their critical velocity; Porter 1996; Porter & Rivinius 2003) of classical Be stars has long been speculated to be the fundamental source driving the production of their geometrically thin circumstellar disks (Struve 1931; Porter & Rivinius 2003), recent photometric surveys (Feast 1972; Grebel et al. 1992; Grebel 1997; Dieball & Grebel 1998; Keller et al. 1999, 2000; Grebel & Chu 2000; Olsen et al. 2001; McSwain & Gies 2005; Wisniewski & Bjorkman 2006) have suggested that secondary mechanisms might contribute to the observed phenomenon. Specifically, Mermilliod (1982), Grebel (1997), Fabregat & Torrejon (2000), and Keller (2004) found that the frequency of the Be phenomenon seems to peak in clusters with a main-sequence turnoff of B1–B2, leading to the suggestion that the Be phenomenon is enhanced with evolutionary age. Several recent observational studies (Grebel et al. 1992; Mazzali et al. 1996; Grebel 1997; Maeder et al. 1999; Keller 2004) have also suggested that the Be phenomenon may be more prevalent in low-metallicity environments, based on comparisons of the fractional Be populations of Galactic, LMC, and SMC clusters.

In Wisniewski & Bjorkman (2006, hereafter WB06), we used a simple two-color diagram (2-CD) technique to identify the fractional candidate Be population of numerous Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and Galactic clusters in an effort to improve the statistical database that has been used to link classical Be disk formation with evolutionary age and/or metallicity. WB06 found evidence that the Be phenomenon develops much earlier than previously predicted by theory (Fabregat & Torrejon 2000), i.e., before the midpoint main-sequence lifetime; furthermore, they found evidence of an additional enhancement in the fractional Be content of clusters with evolutionary age. The increased statistics offered by this work, while confirming the previously suggested trend of an enhancement in the Be phenomenon in low-metallicity environments, lowered the average fractional Be content of SMC clusters from 39% (Maeder et al. 1999) to 32%.

While the 2-CD has been widely used to link evolutionary age and/or metallicity with Be disk formation, it is inherently unclear whether all B-type objects identified as excess H$\alpha$ emitters, i.e., “Be stars,” are truly classical Be stars. It has been noted that other B-type objects, such as Herbig Ae/Be stars, post-main-sequence B[e] stars, and supergiants, may also exhibit H$\alpha$ emission and hence “contaminate” these claimed detections (WB06).

Polarimetry is a tool that has long been used to investigate the circumstellar environments of Be stars (Coyne & Kruzewski...
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TABLE 1

| Cluster | Location | Filter | Age | Date      | Exposure Time |
|---------|----------|--------|-----|-----------|---------------|
| Bruck 60 | SMC      | U      | o   | 2002 Oct 19 | 1200          |
| NGC 330 | SMC      | U      | y   | 2001 Nov 22 | 1200          |
| NGC346  | SMC      | U      | vy  | 2001 Nov 21 | 720           |
| NGC 371 | SMC      | U      | vy  | 2002 Oct 18 | 1200          |
| NGC 456 | SMC      | U      | y   | 2002 Oct 24 | 1200          |
| NGC 458 | SMC      | U      | o   | 2002 Oct 27 | 1200          |
| LH 72   | LMC      | U      | vy  | 2002 Oct 26 | 1200          |
| NGC 1818| LMC      | U      | y   | 2001 Nov 21 | 1200          |
| NGC 1858| LMC      | U      | vy  | 2002 Oct 19 | 1200          |
| NGC 1948| LMC      | U      | y   | 2001 Nov 27 | 1200          |
| NGC 2004| LMC      | U      | y   | 2001 Nov 25 | 900           |
| NGC 2100| LMC      | U      | y   | 2001 Nov 24 | 1200          |

Notes.—We summarize some of the properties of the data presented in this paper. The exposure times listed are the integration time used at each of eight wave-plate positions. The age labels in col. (4), originally defined and discussed in detail in Wisniewski & Bjorkman (2006) correspond to very young (vy) 5–8 Myr; young (y) 10–25 Myr; and old (o) 32–158 Myr.

7 The Cerro Tololo Inter-American Observatory is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under contract with the National Science Foundation (NSF).
data. The $B$, $V$, $R$, and $I$ filters of our 2002 data also had an instrumental polarization consistent with zero (Wisniewski et al. 2003), while the $U$-filter data had an instrumental polarization of $\sim0.1\%$, which was removed from the data.

The reduction of these data began with standard image processing, including bias and flat-field corrections, using standard IRAF\(^8\) techniques. Following this initial processing, aperture photometry was performed for all point sources in each of the eight images of an observation set, using 10 apertures of size $3 \times 12$ pixels for the f/7.5 data and $5 \times 14$ pixels for the f/13.5 data. The linear polarization of each source was extracted from a least-squares solution of the difference amplitudes in the eight wave plate positions ($\psi_i$), using the PCCDPACK software suite (Pereyra 2000; Pereyra & Magalhães 2002). Both the expected photon noise errors and the actual measured errors, defined as the residuals at each wave plate position with respect to the expected $\cos 4\psi_i$ curve, were also calculated. With few exceptions, these two errors were consistent with one another.

### 3. INTERSTELLAR POLARIZATION

The polarization observed in our raw data is comprised of the superposition of an interstellar component, attributable to the dichroic absorption of starlight by partially aligned dust grains along each line of sight, and possibly an intrinsic component, attributable to the asymmetric illumination of circumstellar material and/or the illumination of an asymmetrical distribution of circumstellar material. Characterizing and isolating each of these components, although often technically challenging, yields two unique diagnostics. Isolating the interstellar polarization component can facilitate detailed studies of the local interstellar medium (ISM) and provide constraints on fundamental properties such as grain size distributions and shapes, as well as diagnosing the magnitude and direction of local magnetic fields. Isolating the intrinsic polarization component enables investigations of the distribution and chemistry of scatterers that comprise unresolved circumstellar environments. We stress that characterizing the polarizing agent (i.e., gas or dust) responsible for producing an intrinsic polarization signal is not possible simply via inspection of the wavelength dependence of the vector sum of interstellar plus intrinsic (i.e., the total) polarization data.

Fortunately, our efforts to identify and separate the interstellar and intrinsic polarization components of our data are simplified by the fact that we have observed rich stellar associations. Most of the stars in these clusters should be normal main-sequence stars lacking any type of asymmetrical circumstellar envelope; hence, they should not exhibit an intrinsic polarization component. Furthermore, we can assume that all of our stars are located at the same general distance, since they are members of a cluster population, and that the properties of the interstellar medium do not significantly vary over the angular extent of our clusters. Hence, each cluster in our sample provides us with a multitude of suitable "field stars" whose polarization we can simply average to estimate the interstellar polarization (ISP) along each line of sight, via the commonly used field-star technique (McLean & Brown 1978).

In Figure 1 we show the total $V$-band polarization of all sources in the LMC cluster NGC 1818 having polarimetric signal-to-noise ratios ($p/\sigma_p$) greater than 5.0. The distinctive grouping of most objects in the Stokes $Q-U$ diagram of this figure (Fig. 1a) and the narrow polarization (Fig. 1d) and position angle (Fig. 1c)
histograms demonstrates that most of these objects do lack significant intrinsic polarization components and only have an ISP component. After excluding objects outside of the dominant trends found in these histograms with an iterative method, we calculated the weighted average and standard deviation of these data to determine a preliminary estimate of this cluster’s ISP in each cluster was reasonable. Overplotted on these estimates is a modified Serkowski law (Serkowski et al. 1975) commonly used to parameterize an ISP. Overplotted in Figure 2 is a modified Serkowski law (Serkowski et al. 1975; Wilking et al. 1982) which we deemed best fit the estimates. We extracted the $U$, $B$, $V$, $R$, and $I$ filter polarization associated with this fit and hereafter use these values to describe the ISP of NGC 1818.

![Graph showing wavelength dependence of ISP](image)

Fig. 2.—Observationally derived total ISP estimates for each filter of NGC 1818 plotted as a function of wavelength. The data closely follow a classic Serkowski-law shape (Serkowski et al. 1975), suggesting that our method for determining the ISP in each cluster was reasonable. Overplotted on these estimates is a modified Serkowski law (Serkowski et al. 1975; Wilking et al. 1982) which we deemed best fit the estimates. We extracted the $U$, $B$, $V$, $R$, and $I$ filter polarization associated with this fit and hereafter use these values to describe the ISP of NGC 1818.

The ISP values compiled in Table 2 are relevant to our efforts to isolate the intrinsic polarization components associated with our target stars; however, they do not yet yield any direct information regarding the properties of the interstellar dust grains that reside in their parent LMC and SMC clusters, as these ISP values are comprised of both foreground Galactic ISP and Magellanic Cloud ISP contributions. Following the techniques used by Clayton et al. (1983) and Rodrigues et al. (1997), we used the interstellar polarization maps of Schmidt (1976) to identify and remove this foreground Galactic ISP contribution (see Table 3) and hence determine estimates of the ISP intrinsic to our LMC and SMC clusters (see Table 4). We used a modified Serkowski law (Serkowski et al. 1975; Wilking et al. 1982) to extrapolate these maps over the wavelength range of our data set and assumed a nominal Galactic $\lambda_{\text{max}}$ value of 5500 Å to characterize the parameter $K$. The errors cited in the Galactic polarization maps (Schmidt 1976) and those present in our total ISP estimates (Table 2) were propagated to produce the error estimates cited in Table 4.

Most of the field stars used to derive our total ISP estimates were not highly reddened objects; hence, the intrinsic LMC and SMC ISP values listed in Table 4 all are characterized by modest polarization amplitudes, which are often on the order of the errors of our data. In spite of this fact, trends in these data are clearly present. As expected, the magnitude of $UBVRi$ polarization toward each cluster follows a Serkowski-like wavelength dependence at a wavelength-independent position angle. This lack of position angle rotation indicates that our Galactic interstellar polarization correction was reasonable and that we are looking at a single magnetic field orientation toward each of our clusters. All LMC clusters exhibit similar ISP properties, with polarization magnitudes ranging from $\sim0.2\%$–$0.5\%$ at a position angle of $\sim45^\circ$; similarly, all SMC clusters also exhibit clear evidence of sharing common ISP properties, with polarization magnitudes ranging from $\sim0.3\%$–$0.6\%$ at a position angle of $\sim120^\circ$–$150^\circ$. The shallow curvature of the Serkowski-law dependence of these data, in combination with the moderate level of uncertainty present, make identifying systematic differences in the interstellar dust grain properties of these clusters difficult. The total ISP (Table 2) and SMC ISP (Table 4) of the cluster NGC 330 does, however, show suggestive evidence of being characterized by a short wavelength $\lambda_{\text{max}}$ value of $\sim4500$ Å (Fig. 3). Such an effect is commonly attributed to the presence of small dust grains and has been previously observed in other SMC sight lines (Rodrigues et al. 1997). In a future paper we will examine the wavelength dependence of moderately and

### Table 2: Average Interstellar Polarization

| Cluster     | $P_u$ (%) | $P_B$ (%) | $P_V$ (%) | $P_R$ (%) | $P_I$ (%) | P.A. (deg) | $P_{\text{max}}$ (%) | $\lambda_{\text{max}}$ (Å) | $\delta$ P.A. (deg) | $K$ |
|-------------|-----------|-----------|-----------|-----------|-----------|------------|-----------------------|--------------------------|-----------------------|----|
| Bruck 60    | 0.46 ± 0.18 | 0.51 ± 0.30 | 0.55 ± 0.23 | 0.54 ± 0.19 | 0.48 ± 0.19 | 130 | 0.55 | 5500 | 0 | 0.923 |
| LH 72       | 0.34 ± 0.14 | 0.37 ± 0.12 | 0.40 ± 0.14 | 0.39 ± 0.12 | 0.35 ± 0.14 | 28 | 0.40 | 5500 | 0 | 0.923 |
| NGC 330     | 0.51 ± 0.17 | 0.53 ± 0.16 | 0.52 ± 0.14 | 0.48 ± 0.17 | 0.41 ± 0.17 | 126 | 0.53 | 4500 | 0 | 0.737 |
| NGC 346     | 0.31 ± 0.17 | 0.35 ± 0.18 | 0.32 ± 0.17 | 0.36 ± 0.15 | 0.32 ± 0.19 | 125 | 0.37 | 5500 | 0 | 0.923 |
| NGC 371     | 0.38 ± 0.15 | 0.42 ± 0.16 | 0.45 ± 0.15 | 0.48 ± 0.15 | 0.39 ± 0.15 | 118 | 0.45 | 5500 | 0 | 0.923 |
| NGC 456     | 0.57 ± 0.21 | 0.63 ± 0.24 | 0.67 ± 0.25 | 0.66 ± 0.29 | 0.58 | 147 | 0.67 | 5500 | −8 | 0.923 |
| NGC 458     | 0.33 ± 0.34 | 0.36 ± 0.23 | 0.39 ± 0.22 | ... | 0.34 ± 0.15 | 120 | 0.39 | 5500 | 0 | 0.923 |

NGC 1818.............. 0.52 ± 0.17 | 0.58 ± 0.16 | 0.62 ± 0.15 | 0.61 ± 0.17 | 0.54 ± 0.14 | 39 | 0.62 | 5500 | 0 | 0.923 |
NGC 1858.............. 0.32 ± 0.21 | 0.36 ± 0.15 | 0.38 ± 0.16 | 0.37 ± 0.22 | 0.33 ± 0.17 | 45 | 0.38 | 5500 | 0 | 0.923 |
NGC 1948.............. 0.57 ± 0.19 | 0.64 ± 0.15 | 0.68 ± 0.18 | 0.67 ± 0.17 | 0.59 ± 0.17 | 35 | 0.68 | 5500 | 0 | 0.923 |
NGC 2004.............. 0.32 ± 0.12 | 0.36 ± 0.13 | 0.38 ± 0.15 | ... | 0.33 ± 0.16 | 26 | 0.38 | 5500 | 0 | 0.923 |

Notes.—The Serkowski parameters $P_u$, $P_{\text{max}}$, $\lambda_{\text{max}}$, $\delta$ P.A., and $K$ that best described each of our clusters are tabulated, along with the final ISP values in the $U$, $B$, $V$, $R$, and $I$ filters. The horizontal line separates SMC clusters (above) from LMC clusters (below).
The total polarization vectors of our observations of the LMC cluster NGC 2100 clearly exhibit evidence of a collective, complex morphology (see Fig. 4). While Figure 4 only presents I-band data, all of our other filters exhibit similar alignment patterns. Recall that we expect that most cluster objects should not exhibit an intrinsic polarization component; thus, we suggest that these systematic morphological changes are related to changes in the magnetic field properties within our field of view. A substantial discussion of the magnetic field properties of NGC 2100 is presented in Wisniewski et al. (2007a). For the purposes of the present study, we only discuss our efforts to parameterize and remove the ISP along the line of sight to this cluster.

We identified three spatial regions in our field of view, corresponding to the region around the cluster core, the region to the south of the cluster core, and the region to the north of the core, which displayed unique ISP characteristics. In Figures 5, 6, and 7, we show the B-band polarization vector maps of what we have defined as regions 1, 2, and 3, respectively, in the total ISP along the line of sight to NGC 2100, overlaid on DSS-2 blue images. Having identified these distinct regions, we then extracted total ISP estimates following the technique previously described. We calculated a $\sigma^2$ weighted average of all objects in each filter served as an initial ISP estimate, determined the modified Serkowski-law parameters that best represented the data, as seen in Figure 8 for region 1, and extracted final ISP values (Table 5) for each region from these Serkowski curves. The locations of the candidate Be stars in NGC 2100 were then correlated to these three ISP regions to determine the ISP correction each should receive. We found NGC 2100:KWBBe 102, 630, and 712 resided in area 2, NGC 2100:KWBBe 353, 797, and 1033 resided in area 3, and the rest of the candidate Be stars resided in area 1.

### 4. INTRINSIC POLARIZATION

We subtracted the ISP from the observed polarization to isolate any intrinsic polarization components present. The location of candidate Be stars in our fields of view were identified by careful correlation with literature coordinates and finder charts. Using several PCCDPACK routines, we meticulously examined the extracted polarization for each of the candidate Be stars in our sample to search for undesired contamination by (1) the ordinary or highly reddened objects in our data set to perform a more detailed investigation of the interstellar medium properties of these LMC and SMC clusters, and complement earlier studies that parameterized the ISM properties of other SMC (Rodrigues et al. 1997) and LMC (Clayton et al. 1983) sight lines.

![Fig. 3.—Same as Fig. 2, but for NGC 330. These data, as well as the SMC ISP associated with NGC 330 (see Table 4), are characterized by a $\tau_{min}$ value of $\sim4500$ Å, suggesting the presence of smaller than average dust grains.](image-url)
extraordinary images of nearby objects and (2) cosmic-ray hits or uncorrected bad pixels. The total polarization of all candidate Be stars that did not suffer from these contamination issues are tabulated in Table 6, while the intrinsic polarization of these objects are tabulated in Table 7.

As discussed in the introduction, electron scattering in the pure gas disks of classical Be stars will polarize a small fraction of stellar photons, producing a well-known wavelength-dependent intrinsic polarization signature. We emphasize that as polarization is a vector quantity, identifying these signatures (1) is only possible via inspection of intrinsic polarization data and (2) requires either the simultaneous inspection of both the wavelength dependence of the polarization magnitude and position angle or, alternatively, inspection of the behavior of the intrinsic data on a Stokes $Q-U$ diagram. An observed wavelength-independent intrinsic polarization magnitude and position angle across the entire $UBVRI$ wavelength regime is the expected signature of pure ES, such as that expected from a gaseous classical Be disk. Moreover, pre- or postscattering absorption will superimpose the wavelength-dependent signature of hydrogen opacity on this signal, creating a “sawtooth” polarization signature (Bjorkman 2000) if enough absorption events occur. Specifically, this sawtooth signature...
includes the presence of abrupt jumps in the magnitude of intrinsic polarization at the Balmer and Paschen limits, as well as a wavelength-independent intrinsic polarization position angle across the entire $UBVRI$ wavelength regime. Examples of these two signatures of classical Be circumstellar disks are given in Figure 9, which presents multiphase observations of the known classical Be star $\pi$ Aquarii as observed by the University of Wisconsin’s HPOL spectropolarimeter.

We have contemporaneously analyzed the Stokes $Q-U$ diagrams of all candidate Be stars’ total and intrinsic polarization components to search for evidence of these signatures. We have developed a conservative four-point classification scale to rank the likelihood that candidate Be stars are truly classical Be stars. Results of this classification are summarized in Table 8 for individual objects and in Table 9 for the net results of entire clusters. The design of our classification system emphasized the identification of objects exhibiting a sawtooth intrinsic polarization signature and a pure ES signature across the entire $UBVRI$ wavelength regime. Specifically, we defined our classification system by:

**Type 1**—objects that are *most likely* classical Be stars;

**Type 2**—objects whose polarimetric properties are *not inconsistent* with those expected from classical Be stars;

**Type 3**—objects that are *unlikely* to be classical Be stars; and

**Type 4**—objects that are *highly unlikely* to be classical Be stars.

Stars in our sample that displayed, to within 3 $\sigma$, a sawtooth-like polarization Balmer jump (BJ) along with a wavelength-independent polarization position angle across the entire range of available data (see Fig. 10) were assigned a designation of type 1. We claim that all type 1 objects are most likely classical Be stars. Note that in § 5.3.1 we offer a detailed discussion of other objects that could exhibit somewhat similar behavior over part of the $UBVRI$ wavelength regime. However, as we discuss in § 5.3.3, analysis of ancillary data demonstrates that it is highly dubious that stars classified as type 1 polarimetric sources are anything other than classical Be stars.

We assigned a designation of type 2 to objects whose polarimetric properties were not inconsistent with that expected from a classical Be star-disk system. As discussed above, classical Be disks of sufficiently low density will not leave an imprint of hydrogen opacity in their intrinsic polarization signals; hence, stars that exhibited, to within 3 $\sigma$, a wavelength-independent ES polarization signature (see Fig. 11) received a designation of type 2. A small number of objects exhibited a nearly wavelength-independent polarization magnitude along with a minor wavelength dependence in their polarization position angles; we designated these objects as type 2, as we believe such stars most likely are exhibiting ES signatures modified by a slight under- or overcorrection of their ISP components. We cannot rule out the possibility that this minor wavelength dependence might also be produced by the additional presence of an optically thin dust disk, as is present in post-main-sequence B[e] stars (Magalhães 1992; Melgarejo et al. 2001). However, as we show in § 5.3.3, analysis of ancillary data demonstrate that most type 2 objects that we claim exhibit ES signatures are likely to be classical Be stars and substantially less likely to be systems characterized by composite gas-plus-dust disks (i.e., Herbig Ae/Be, B[e] stars). Finally, we assigned all objects that appeared to be intrinsically unpolarized (<0.3% polarization), to within 3 $\sigma$, a type 2 designation, as this is the expected signature of pole-on or nearly pole-on classical Be stars. We caution the reader that we are not 100% certain that these unpolarized objects are classical Be stars, as (1) stars without gaseous disks, spurious detected as excess H$_2$ emitters on 2-CDs, will also exhibit zero net intrinsic polarization and (2) the noise present in the observations of fainter targets may preclude us from clearly identifying these non-Be stars as “contaminants.”

We assigned the designation of type 3 to type 4 to objects whose polarimetric polarization, to within 3 $\sigma$, appeared to be inconsistent with the aforementioned signatures expected from a classical Be star-disk system (see e.g., Fig. 12). We briefly discuss some of the major types of atypical polarimetric signatures we observed.

In Table 8 we assigned a designation of type 3 to 4 to several objects whose intrinsic polarization exhibited signs of a 90° position angle reversal (Fig. 14), which is a signature of a dusty bipolar nebula geometry (see § 5.3.1; see also Schmidt et al. 1992; Schulte-Ladbeck et al. 1992). From an inspection of the Stokes $Q-U$ diagram of such an object (Fig. 14), it is clear that even if our initial ISP correction was grossly miscalculated, the wavelength-dependent polarization would still be inconsistent with that expected from classical Be stars. While it would be interesting to

### TABLE 5

| Cluster | $P_n$ (%) | $P_b$ (%) | $P_e$ (%) | $P_r$ (%) | $P_i$ (%) | P.A. (deg) | $P_{max}$ (%) | $\lambda_{max}$ (\AA) | $\delta$ P.A. (deg) | $K$ |
|---------|-----------|-----------|-----------|-----------|-----------|------------|---------------|-----------------|-----------------|-----|
| NGC 2100 area 1 | 1.32 | 1.41 | 1.44 | 1.37 | 1.20 | 139 | 1.45 | 5000 | 0 | 0.83 |
| NGC 2100 area 2 | 1.26 | 1.35 | 1.37 | 1.31 | 1.14 | 100 | 1.38 | 5000 | 0 | 0.83 |
| NGC 2100 area 3 | 1.64 | 1.69 | 1.65 | 1.54 | 1.32 | 78 | 1.70 | 4500 | 0 | 0.737 |

**Note.**—A summary of the total interstellar polarization values toward NGC 2100 for the three distinct spatial regions identified within the field of view of our NGC 2100 data set.
further probe the circumstellar environments of such objects with follow-up investigations, for the purposes of this paper we merely remark that they are unlikely to be classical Be stars.

Several of our candidate Be stars exhibited very large (1%–3.5%), complex intrinsic polarization signatures (see Fig. 13). Given the steep drop in their polarization magnitude at short optical wavelengths, along with subtle indications of a corresponding position angle rotation, it is possible that these objects are characterized by dusty bipolar nebulae whose polarization signature exhibits a position angle reversal at UV wavelengths, similar to HD 45677 (Schulte-Ladbeck et al. 1992). Alternatively, the polarization of these objects could be interpreted as following a Serkowski-like wavelength dependence characterized by a large $\lambda_{\text{max}}$ value. As our data have already been corrected for the average ISP associated with each of our clusters, this latter interpretation would require these objects to be situated in region of patchy dust, likely populated by larger grains, given the long wavelength values of $\lambda_{\text{max}}$, i.e., $>7000\,\text{Å}$ in Figure 13 (Rodrigues et al. 1997; Whittet et al. 1992). Serkowski et al. (1975) described the expected magnitude of interstellar polarization by the formula

$$3E_B - V \leq P_{\text{max}} \leq 9E_B - V;$$

hence, an additional reddening of 0.3–1.0($B-V$) would be required to produce the measured $P_{\text{max}}$ of these objects, $\sim3\%$. The observed colors of at least some of these objects (NGC 1948:KWBBe 98, $V-I = 0.67$; Keller et al. 1999) is likely sufficient to produce the amount of purported additional ISP, although other objects (NGC 1948:KWBBe 246, $V-I = 0.05$; Keller et al. 1999) clearly do not meet this criteria. While follow-up optical or infrared spectroscopy of these anomalous candidates would help to determine whether they exhibit a dusty bipolar nebula geometry or are located in a region of patchy dust, for the purpose of this paper we merely stress that it is clear that these objects are not likely to be classical Be stars.

![Fig. 9.](image)

We now offer discussion of the polarimetric properties of candidate Be stars in individual clusters. Recall that all candidates that exhibited evidence of contamination, predominantly from nearby neighbors, have been excluded from our analysis. We further note that the effective limiting magnitude of our polarimetric data set was lower (i.e., brighter) than that considered in WB06.

### 4.1. LMC Clusters

#### 4.1.1. NGC 1818

Keller et al. (1999) identified 40 candidate Be stars associated with the LMC cluster NGC 1818 and its surrounding field. The cluster is densely populated, and because of image overlap issues we were only able to retrieve polarimetric information for 18 of these candidate Be stars. Four of these 18 (22%) showed intrinsic polarization BJ signatures, NGC 1818:KWBBe 69, 82, 137, and 243. We classified 12 of the 18 candidates (67%) as type 2 objects, and found that 5 of the type 2 objects (i.e., 5 of the 18 stars, 28%, in the total population) exhibited clear evidence of an ES polarization signature. Two of the 18 candidates (11%), NGC 1818:KWBBe 47 and 381, were deemed unlikely to be classical Be stars. While the $B$, $V$, $R$, and $I$ filter polarizations of NGC 1818:KWBBe 47 were consistent with an ES signature, the $U$ filter exhibited a significant position angle rotation that was inconsistent with an ES origin. Although noisy, the observation of NGC 1818:KWBBe 381 also did not follow an ES wavelength dependence, prompting us to assign it an “unlikely Be star” designation.

#### 4.1.2. NGC 1948

Keller et al. (1999) identified 27 candidate Be stars associated with the cluster NGC 1948 and its nearby field. We were able to extract polarimetric information on 22 of these candidates from our data set. Six of these 22 candidates (27%) exhibited a polarization BJ, NGC 1948:KWBBe 71, 75, 102, 153, 172, and 240.

### Table 6

| Candidate Be Star | Filter | $P$ (%) | P.A. (deg) | $Q$ (%) | $U$ (%) | Error (%) |
|------------------|--------|---------|-----------|---------|---------|----------|
| Bruck 60:WBBe 1  | $u$    | 1.75    | 107.3     | -1.44   | -0.99   | 0.61     |
|                  | $b$    |         |           |         |         |          |
|                  | $v$    | 1.33    | 113.7     | -0.90   | -0.98   | 0.30     |
|                  | $r$    | 1.33    | 117.6     | -0.76   | -1.09   | 0.35     |
|                  | $i$    |         |           |         |         |          |

**Notes.**—The total polarization (i.e., interstellar plus intrinsic components) of one candidate Be star investigated in this study is tabulated. Table 6 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

### Table 7

| Candidate Be Star | Filter | $P$ (%) | P.A. (deg) | $Q$ (%) | $U$ (%) | Error (%) |
|------------------|--------|---------|-----------|---------|---------|----------|
| Bruck 60:WBBe 1  | $u$    | 1.46    | 100.9     | -1.36   | -0.54   | 0.61     |
|                  | $b$    |         |           |         |         |          |
|                  | $v$    | 0.91    | 104.4     | -0.80   | -0.44   | 0.30     |
|                  | $r$    | 0.88    | 110.0     | -0.67   | -0.56   | 0.35     |
|                  | $i$    |         |           |         |         |          |

**Notes.**—The intrinsic polarization of one candidate Be star investigated in this study is tabulated. Table 7 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
We classified 12 of the 22 candidates (55%) as type 2 objects, and found that 6 of the type 2 objects (i.e., 6 of the 22, 27%, in the total population) exhibited a definite ES polarization signature, NGC 1948:KWBBe 62, 92, 101, 157, 326, and 790. We note that NGC 1948:KWBBe 92 does show a hint of a small polarization BJ; however, we opted to describe its polarization more conservatively, i.e., as having an ES signature. We found that 4 of the 22 stars (18%) had polarimetric properties which suggested that they were unlikely to be classical Be stars. As previously discussed, 3 of these stars, NGC 1948:KWBBe 98, 183, and 246 exhibited intrinsic polarization signals that seemed to follow a Serkowski-like wavelength dependence. NGC 1948:KWBBe 91 was also deemed unlikely to be a classical Be star due to the wavelength-dependent nature of its polarization position angle.

### 4.1.3. NGC 2004

Keller et al. (1999) identified 67 candidate Be stars associated with the LMC cluster NGC 2004 and its surrounding field. We extracted polarimetric information for 43 of these candidates and found that 9 of the 43 (21%), namely, NGC 2004:KWBBe 50, 87, 96, 103, 106, 152, 211, 347, and 377, showed an intrinsic polarization BJ. Twenty-eight of the 43 candidates (65%) were classified as type 2 objects, and note that 10 of these 28 type 2 objects (i.e., 10 of the 43, 23%, in the total population), NGC 2004:KWBBe 91, 203, 276, 323, 344, 441, 624, 717, 1175, and 1421, exhibited an ES polarization signature. We found 6 of the 43 (14%) candidates in NGC 2004 were unlikely to be classical Be stars based on their intrinsic polarization. Of these objects, we note that the three filters of polarization extracted for NGC 2004:KWBBe 1315 show suggestive evidence of a polarization position angle flip, a feature that is not expected in classical Be star-disk systems.

#### 4.1.4. LH 72

WB06 identified 50 candidate Be stars in the LMC cluster LH 72 and designated 11 of these detections as tentative. We were able to obtain polarimetric information for 34 of these stars: 1 of the 34 (3%), LH 72:WBBE 5, showed a polarization BJ and is most likely a bona fide classical Be star. We classified 22 of the 34 (65%) stars as type 2 objects, and found 5 of these 22 type 2 objects (i.e., 5 of the 34, 15%, of the total population), LH 72:WBBE 13, 15, 26, 27, and 33 exhibited an ES polarization signature. We suggest that 11 of the 34 (32%) of candidates in LH 72 are unlikely to be classical Be stars based on their intrinsic polarization properties. Of these unlikely Be stars, we found that the intrinsic polarization of LH 72:WBBE 9 followed a Serkowski-like wavelength dependence, with a $\lambda_{\text{max}}$ value >6000 Å. We extracted polarimetric information for 7 of the 11 stars designated as possible candidate Be stars by WB06. Five of these 7 stars were classified as type 2 objects, while 2 of the 7 appear unlikely to be classical Be stars based on their intrinsic polarization signatures.

#### 4.1.5. NGC 1858

WB06 identified 39 candidate Be stars in the LMC cluster NGC 1858, and we were able to extract polarimetric information for 27 of these 39 stars. Three of the 27 (11%), NGC 1858:WBBE 6, 9, and 20, exhibited polarization BJs. We classified 13 of the 27 (48%) as type 2 objects, and found 2 of these 13 type 2 stars (i.e., 2 of the 27, 7%, of the total population) exhibited an ES polarization signature. Eleven of the 27 (41%) candidates in NGC 1858...
appear unlikely to be classical Be stars based on their polarimetric signatures. As previously discussed, 2 of these unlikely Be stars, NGC 1858:WBBe 3 and 12 had an intrinsic polarization that follows a Serkowski-like wavelength dependence, characterized by a long $\lambda_{\text{max}}$ value. Four of the 39 photometrically identified candidate Be stars in NGC 1858 were judged to be possible detections in WB06; we were able to detect 3 of these 4 polarimetrically. We classified 2 of the 3 as type 2 objects, and the remaining object, NGC 1858:WBBe 9, as a type 1 object.

4.1.6. NGC 2100

Keller et al. (1999) identified 61 candidate Be stars associated with the LMC cluster NGC 2100. We were able to extract polarimetric information for 35 of the 61 candidates (57%). Eight of the 35 stars (23%), NGC 2100:KWBBe 79, 97, 436, 619, 635, 705, 770, and 797, exhibited polarization BJs and hence are most likely to be classical Be stars. Twenty of the 35 stars (57%) were classified as type 2 stars, and we found that 7 of these 20 type 2 stars (i.e., 16 of the 35, 46%, of the total population) exhibited an ES intrinsic polarization signature. We suggest that 7 of the 33 candidates in NGC 2100 are unlikely to be classical Be stars based on their observed intrinsic polarization signatures. Note that the intrinsic polarization of NGC 2100:KWBBe 321 seems to follow a Serkowski-like wavelength dependence, while the unique intrinsic polarization signatures of NGC 2100:KWBBe 111 and 219 (Fig. 14) suggest that these objects might be dust-disk systems.

4.2. SMC Clusters

4.2.1. NGC 346

Keller et al. (1999) identified 48 candidate Be stars in the vicinity of the SMC cluster NGC 346; we have obtained polarimetric information for 33 of these objects. Eight of the 33 objects (24%), NGC 346:WBBe 85, 93, 191, 236, 374, 445, 468, and 529, exhibited polarization BJs and hence are most likely classical Be stars. We classified 22 of the 33 stars (67%) as type 2 stars and found that 7 of these 22 type 2 objects (i.e., 7 of the 33, 21%, of the total population) exhibited a clear ES intrinsic polarization signature. We suggest that 3 of the 33 candidates in NGC 346 are unlikely to be classical Be stars based on their polarimetric signatures. Although not detected via our polarimetric survey, we note that NGC 346:KWBBe 13 and NGC 346:KWBBe 200 should not be considered to be classical Be stars; the former (NGC 346:KWBBe 13) is the well-known Wolf-Rayet/LBV HD 5980 and the latter (NGC 346:KWBBe 200) has

![Fig. 10.—Intrinsic polarization of NGC 371:WBBe18 exhibiting the sawtooth-like polarization signature characteristic of classical Be stars. Such objects were assigned a designation of type 1 to indicate that they are definitely classical Be stars.](image1)

![Fig. 11.—Intrinsic polarization of NGC 371:WBBe21 clearly exhibiting a wavelength-independent ES polarization signature. Such objects were assigned a designation of type 2 to indicate that they are not inconsistent with being classical Be stars.](image2)
recently been shown to be the fifth known Be[e] in the SMC (Wisniewski et al. 2007b).

4.2.2. **NGC 371**

WB06 identified 129 candidate Be stars in NGC 371. We have obtained polarimetric information for 73 of these targets and found that 10 of these 73 stars (14%), NGC 371:WBBe 2, 3, 4, 5, 6, 10, 13, 18, 24, and 31, exhibited polarization BJ, indicating that they are most likely classical Be stars. We classified 49 of the 73 stars (67%) as type 2 objects and remark that 6 of these 49 type 2 stars (i.e., 6 of the 73, 8%, of the total population) exhibited an ES polarization signature. Note that many of the fainter candidate Be stars included in our 74 detections were not observed at high signal-to-noise levels; thus, for most of these objects we can only say that to within 3\( \sigma \), their polarimetric properties are not inconsistent with those of classical Be stars. We suggest that 14 of the 73 (19%) candidates in NGC 371 are unlikely to be classical Be stars based on their polarimetric properties. WB06 suggested that 11 of the 130 photometrically identified candidates should be viewed as "possible detections"; however, we were only able to extract polarimetric information for 2 of these 11 objects, NGC 371:WBBe 64 and 87. We classified both as type 2 stars.

4.2.3. **Bruck 60**

We were able to extract polarimetric information for 18 of the 60 candidate Be stars identified photometrically by WB06. We found 1 of the 18 (6%), Bruck 60:WBBe 6, showed a polarization BJ, while we classified 11 of the 18 stars (61%) as type 2 objects. Eight of these 11 type 2 stars (i.e., 8 of the 18, 44%, of the total population) exhibited an ES intrinsic polarization signature. We suggest that 6 of the 18 (33%) candidates in Bruck 60 are unlikely to be classical Be stars based on their polarimetric signatures. WB06 noted that 5 of the 26 photometrically identified candidate Be stars in Bruck 60 should be considered "possible detections." We were only able to detect 1 of these 5 stars polarimetrically, Bruck 60:WBBe 21, and classified it as a type 2 object that exhibited clear evidence of an ES polarization signature.

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**Fig. 12.** The intrinsic polarization of NGC 371:WBBe47 is not consistent, to within 3\( \sigma \), with that expected from a classical Be star. Such objects would receive a designation of type 3 or type 4, depending on the severity of their deviation from any of the expected polarimetric signatures. These objects (especially those which receive a type 4 designation) provide strong evidence that the 2-CD technique can misidentify classical Be star-disk systems.

**Fig. 13.** The intrinsic polarization of NGC 1948:KWBBe 246 follows a complex wavelength dependence. The optical polarization appears to decrease and position angle increase at short wavelengths. Objects that have dusty plus gaseous disks, such as HD 45677 (Schulte-Ladbeck et al. 1992), exhibit similar optical polarimetric behavior, suggesting that NGC 1948:KWBBe 246 and similar objects in our sample might also be characterized by such disks. Alternatively, the wavelength dependence of these data also resembles a Serkowski-like behavior (Serkowski et al. 1975), which, as discussed in §4, might indicate that some of these types of objects are characterized by abnormal interstellar dust conditions.
Twenty-three candidate Be stars in NGC 456 were identified in the photometric survey of WB06, and we were able to extract polarimetric information for 14 of these 23 candidates. Although we did not observe any objects with polarimetric BJs, we did classify 9 of the 14 stars (64%) as type 2 objects. One of these 9 type 2 stars (i.e., 1 of the 14, 7%, of the total population), NGC 456:WBBe 1, exhibited an ES polarization signature. We suggest that 5 of the 14 (36%) candidates in NGC 456 are unlikely to be classical Be stars based on their observed intrinsic polarimetric components. WB06 suggested that 1 of NGC 456's 23 photometrically identified candidate Be stars should be viewed as a "possible detection": we marginally detected this object, NGC 456:WBBe 21, and suggest that it is unlikely to be a classical Be star.

Keller et al. (1999) identified 76 candidate Be stars in the vicinity of NGC 330, and we were able to extract polarimetric information for 41 of these objects. While we did not observe any of the detected candidates to have a polarimetric BJ, we did classify 24 of the 41 (59%) candidates as type 2 stars, and we note that 9 of these 24 type 2 objects (i.e., 9 of the 41, 22%, of the total population) exhibited ES polarimetric signatures. We suggest that 17 of the 41 (41%) candidates are unlikely to be classical Be stars based on their intrinsic polarimetric signatures.

5. DISCUSSION

5.1. Analysis of Intrinsic Polarization Statistics

It is clear from Table 9 that the percentage of SMC and LMC candidate Be stars that exhibit polarization BJs or ES signatures or were deemed unlikely to be classical Be stars varies significantly from one cluster to the next. To better assess the global trends of our data set, we extracted simple statistical mean and median values from Table 9, as summarized in Table 10. From Table 10, we see that at least 25% of our data set is populated by objects that appear unlikely to be classical Be stars. The presence of such a large number of likely contaminants is interesting, as it confirms one of the initial hypotheses of this project: it is dangerous to assume a priori that all objects identified as excess H\alpha emitters via 2-CD surveys are classical Be stars. We thus suggest that caution should be exercised when attempting to ascertain the role evolutionary age and/or metallicity play in

| Cluster          | Mean BJ (%) | Median BJ (%) | Mean ES (%) | Median ES (%) | Mean Unlikely (%) | Median Unlikely (%) |
|------------------|-------------|---------------|-------------|---------------|-------------------|---------------------|
| Very young       | 13          | 13            | 13          | 12            | 25                | 26                  |
| Young            | 13          | 13            | 21          | 22            | 26                | 20                  |
| SMC              | 7           | 3             | 17          | 15            | 30                | 35                  |
| LMC              | 18          | 22            | 24          | 25            | 23                | 19                  |
| ALL SMC+LMC      | 13          | 13            | 21          | 22            | 26                | 26                  |

Notes.—Statistical averages of data listed in Table 9 are presented. Clusters were grouped according to age (very young and young) as well as metallicity (SMC and LMC). The final entry labeled "ALL" denotes a global average of all SMC and LMC cluster data regardless of age or metallicity.
the development of the Be phenomenon purely via the analysis of 2-CD data.

Assuming that these objects are truly contaminants, we recalculated the statistics of our intrinsic polarization data set after removing these objects from consideration. The results of this exercise are listed in Table 11. The median prevalence of polarization BJs in our SMC/LMC data set is typically between 20% and 25% (Table 11). Polarization BJs appear to be significantly less prevalent in our SMC clusters (4%) than in our LMC clusters (25%); however, this statistic is strongly influenced by the null detection of such signatures in three SMC clusters.

Since 1989, the HPOL spectropolarimeter (Wolff et al. 1996) mounted on the University of Wisconsin’s Pine Bluff Observatory (PBO) has been monitoring the optical spectropolarimetric properties of a sample of 73 known Galactic Be stars, and it provides a statistically significant polarimetric data set, which we use to aid the interpretation of our results. As yet, most of the ~800 HPOL observations of classical Be stars have not had their ISP components identified and removed; hence, we cannot readily compare their intrinsic polarization characteristics to our data. However, we can determine the prevalence of polarization BJs in the HPOL database. Data obtained prior to 1995 have been compiled in catalog form by Bjorkman et al. (2000) and observations characterized by a polarization BJ have already been flagged in the catalog. We have similarly analyzed all observations obtained from 1995 to 2004 to identify the presence of polarimetric BJs in these data. We then compiled all HPOL observations of individual classical Be stars into two categories: (1) classical Be stars that had never exhibited a polarimetric BJ in any PBO observation and (2) classical Be stars that had exhibited a polarimetric BJ in at least one observation. The results of this classification procedure are given in Table 11.

We found that 31 of the 73 (42%) observed Galactic Be stars exhibited a polarimetric BJ for at least part of the time frame of the HPOL survey. Among early-type Be stars (O9–B5) in the HPOL database, 22 of 45 (49%) exhibited polarimetric BJs. Note that further restricting the sample to include only O9–B3 type Be stars does not appreciably affect the observed prevalence of polarization BJs, as 17 of 40 (43%) exhibited such a signature. In contrast, the prevalence of polarization BJs does seem to be noticeably lower for later type (B6–A0) Be stars, as we found that only 8 of 26 (31%) exhibited evidence of a polarimetric BJ.

The frequency of polarization BJs appears to decrease with metallicity: ~45% of Galactic Be stars in the HPOL database, ~25% of LMC Be stars from the present study, and ~4% of SMC Be stars from the present study exhibit polarization BJs. We suggest several possible explanations for these results.

1. It is possible that the average disk properties of classical Be stars are fundamentally different in the low-metallicity environments of the SMC and LMC as compared to our Galaxy. The presence of intrinsic polarization in classical Be stars, as well as its wavelength dependence, is a function of disk inclination angle, disk density, and the effective temperature of disk material. Thus, the observed lower frequency of polarization BJs in our data suggest either that it might be harder to form massive disk systems in low-metallicity environments or that the average disk temperature is higher in these lower metallicity environments, hence decreasing the amount of pre and postscattering absorption by neutral H I.

2. Our polarimetric observations provided a one-time sampling of LMC and SMC candidate Be stars, while the HPOL survey obtained a larger number of observations, albeit at quasi-random intervals, of a population of known Be stars. Owing to the variable nature of the Be phenomenon, we do not a priori know how often any individual Be star will exhibit any of the possible polarization signatures; hence, the different sampling errors associated with these two databases might explain at least some of the observed differences in the polarization BJ frequencies.

3. The statistics presented in Table 11 were based on removing a significant number of objects deemed unlikely to be classical Be stars from consideration, i.e., type 3 and type 4 objects. Recall, however, that our definition of type 2 objects only required their polarimetric properties to be not inconsistent with those expected from classical Be stars. It is possible that a population of contaminants, either (1) unpolarized objects that are not pole-on or near pole-on classical Be stars or (2) nonclassical Be stars that were not identified as such due to low data quality, still reside in our collection of type 2 objects, and hence cause us to underestimate our polarization BJ fraction frequency. If such a scenario is true, it would further suggest that extreme caution should be exercised when assessing the nature of stellar populations purely via the use of photometric 2-CDs.

5.2. Identification of Contaminants in 2-CD Detected Candidate Be Stars

WB06 identified a large number of B-type objects having excess Hα emission via photometric 2-CDs and suggested that these stars be classified as candidate Be stars. D. Gies (2006, personal communication) noted that several candidate Be stars in the WB06 data set had colors redder than that expected from classical Be stars and suggested that the frequency of observed blue (or red) excess Hα emitters in the two-color diagrams presented in WB06 increased with the total number of stars of a given color range. Furthermore, he postulated that if these red excess emitters were (1) a manifestation of extremely young stars with their birth disks still intact, (2) red-type giants or supergiants, or (3) false detections owing from the effects of bright background H α emission, measuring the prevalence of these excess emitters could serve as an estimate of the number of contaminants that affect the blue population of excess Hα emitters, i.e., the candidate Be star population.

We examined the 2-CD photometry of six clusters, common to both this survey and that of WB06 and spanning a wide range of ages (very young, young, old, WB06) and metallicities (SMC, LMC), and determined the frequency of excess red-type Hα emitters relative to the total number of red-type stars. We restricted our analysis such that the magnitude of $B-V$ colors used to identify
candidate Be stars in each cluster (i.e., $-0.3 < B - V < 0.2$ in NGC 458; WB06) matched the range of $B - V$ colors used to study the frequency of red-type excess H$\alpha$ emitters (i.e., $0.2 < B - V < 0.7$ for NGC 458). Furthermore, we adopted the same (R-H$\alpha$) cutoffs delineating excess emitters from normal stars for each cluster as used by WB06. The results of this exercise are tabulated in column (2) of Table 12. Interestingly, with few exceptions, the frequency of potential contaminants implied by this technique is generally consistent with the minimum rate of contamination derived from our polarization results (see col. [3] of Table 12, col. [6] of Table 9), i.e., the candidates we assigned a type 4 classification. Clearly this photometric contamination check cannot provide a diagnostic on the Be classification of individual objects, unlike our polarimetry; however, we suggest that this technique might provide a rough estimate of the role of contaminants in cases in which detailed follow-up observations have not been made or are unfeasible.

### 5.3. The Evolutionary Status of Excess H$\alpha$ Emitters in Very Young (5–8 Myr) Clusters: Early-Type Classical Be Stars or Early-Type Herbig Be Stars?

One of the interesting results presented in WB06 was the identification of candidate Be stars in clusters of age 5–8 Myr, in an abundance similar to the general frequency of the Be phenomenon in our Galaxy, ~17%. However, it was uncertain based on those results whether the detected excess H$\alpha$ emitters (1) were true classical Be star-disk systems; (2) were B-type objects that still possessed remnant star formation disks, i.e., Herbig Be stars; or (3) merely had diffuse H$\alpha$ nebulosity coincidentally associated with them. Our intrinsic polarimetric data set affords us the opportunity to further constrain the evolutionary status of candidate Be stars in four clusters of age 5–8 Myr, LH 72, NGC 1858, NGC 346, and NGC 371.

#### 5.3.1. Intrinsic Polarization Signatures of Dust versus Gas Disks

As discussed in the introduction, § 4, and references therein, it is well accepted that classical Be stars are characterized by geometrically thin gas disks and that the mechanism responsible for producing their intrinsic polarization is ES. Herbig Be stars are more complex systems in that their circumstellar environments contain both gas and dust. The dominant polarigenic mechanism in Herbig Be stars is well established to be scattering by dust, as outlined in the review papers of Bastien (1988), Grinin (1994), and Waters & Waelkens (1998), and numerous references therein. While Herbig Be and classical Be stars exhibit some similar observational traits, such as the presence of an intrinsic, often variable, polarization component (Vrba et al. 1979; Quirenbach et al. 1997; Vink et al. 2002; Bjorkman & Meade 2005; Bjorkman 2006), the different scattering mechanisms that characterize Herbig Be versus classical Be stars manifest themselves in several observational manners. The magnitude of linear polarization of classical Be stars is typically of order 1% or less (Bjorkman et al. 2000), whereas the average (~3%) and maximum (14.5%) polarization observed in Herbig Ae/Be stars is clearly much larger (Tamura & Fukagawa 2005). More importantly, the different scattering mechanisms that dominate in each of these star-disk systems will produce a different wavelength dependence in these stars’ intrinsic polarization.

The characteristic wavelength-dependent intrinsic polarization signature of classical Be stars has already been documented in § 4. Herbig Be stars are not known to exhibit any singular “characteristic” intrinsic polarization behavior (see, e.g., Vrba et al. 1979; Bastien 1988; Meyer et al. 2002); the grain chemistry, grain size distribution, and relative size and extent of the gas and dust disks/envelopes of individual Herbig Be systems likely contributes to the heterogeneous mix of observed intrinsic polarization. Some typical intrinsic polarization trends are observed in Herbig Ae/Be stars, however, most notably rotations (and dramatic 90° reversals) in the intrinsic polarization position angle (Schmidt et al. 1992; Bjorkman et al. 1995, 1998; Meyer et al. 2002). We remark that several works in the literature that describe and interpret the wavelength dependence of intrinsic polarization from Herbig Be stars, and at times attempt to draw parallels with the intrinsic polarization behavior of classical Be stars, should be viewed with caution. For example, as noted by Bastien (1988) both Vrba (1975) and Garrison & Anderson (1978) employ dubious assumptions in their efforts to constrain the interstellar polarization along the line of sight to their Herbig Be stars, and as such the wavelength dependence of the “intrinsic” polarization they report is likely inaccurate. Similarly, the discussion of the wavelength dependence of intrinsic polarization of the Herbig Be star BD +61 154 in Vrba et al. (1979); see their Fig. 2) ignores the wavelength dependence of the intrinsic polarization position angle. The ~40° intrinsic polarization position angle rotation from the B to I filter in these data is inconsistent with the expected signature of a pure gas disk system; the wavelength dependence of intrinsic polarization from this Herbig Be star is not similar to that observed for classical Be stars.

Although dust scattering is the dominant polarigenic agent for Herbig Be stars, it is still possible to detect evidence of the gaseous inner disk component of some of these systems via polarimetry (Vink et al. 2002; Meyer et al. 2002; Oudmaijer et al. 2005). For example, Meyer et al. (2002) present intrinsic spectropolarimetry of the Herbig Be star MWC 349A, covering the wavelength range ~5000–10500 Å ($V', R$, and $I$ filters), which exhibits both line depolarization effects and a Paschen polarization jump (see their Fig. 7), similar to that observed in the classical Be star ζ Tau (Wood et al. 1997). Meyer et al. (2002) suggest ES as the mechanism responsible for producing these specific features. Evidence of the dusty component of MWC 349A’s composite disk is also evident in these data. Specifically, the 30°–40° rotation in the intrinsic continuum polarization position angle, beginning at ~6200 Å and extending to the blue edge of the available data, ~5000 Å indicates the presence of an additional scattering mechanism that becomes more pronounced at shorter wavelengths, i.e., dust scattering.

Based on the available literature, we are aware of no compelling examples of Herbig Be stars whose intrinsic polarization

### Table 12: Frequency of Contaminants in Be Populations Identified via 2-CDS

| Cluster   | Analysis of 2-CD Data (%) | Analysis of Polariometry (%) |
|-----------|---------------------------|-------------------------------|
| Bruck 60  | 14                        | 33                            |
| NGC 371   | 11                        | 19                            |
| NGC 456   | 10                        | 36                            |
| NGC 458   | 38                        | 40                            |
| LH 72     | 25                        | 32                            |
| NGC 1858  | 42                        | 41                            |

Notes.—The possible rate of contamination of classical Be star detections extracted from photometric two-color diagrams. As discussed in § 5.2, col. (2) represents the frequency of red-type excess H$\alpha$ emitters, which we suggest might be an appropriate proxy of the frequency of B-type excess H$\alpha$ emitters which are not classical Be stars. Col. (3): reproduction of col. (6) in Table 9 and illustrates the frequency of 2-CD contaminants as derived from polarimetric observations of candidate Be stars.
magnitude and position angle fully follow the known $UBVRI$ behavior of classical Be stars. While it is neither typical nor likely, we cannot rule out the possibility that one could in principle observe a BJ signature in the polarization magnitude of some Herbig Be stars, as these systems do have composite gas-plus-dust disks. However, as dust scattering is the dominant polarogenic scattering agent in Herbig Be stars, it is dubious that the entire $UBVRI$ intrinsic polarization magnitude and position angle of such systems would exhibit no evidence of a non-ES component. Moreover, as astutely pointed out by our referee, it would be even more unlikely to observe one of our “type 2 ES signatures” in any Herbig Be star, unless the dust grain chemistry and size distribution conspired to produce gray scattering.

Hence, the $UBVRI$ spectral range of the intrinsic polarization data presented in this paper enables us to discriminate deviations from a pure ES signature over a broad spectral range. This allows us to differentiate Herbig Be stars analogous to MWC 349A, whose gaseous disk dominates a portion of the optical polarimetric regime, and Herbig Be stars, whose dust disks dominate the optical polarimetric regime, from classical Be stars.

5.3.2. Nebular Origin?

As noted in WB06, many of the candidate Be stars identified in clusters of age $5–8$ Myr reside nearby or even within regions characterized by diffuse nebular emission. We consider whether the observed characteristic polarimetric signatures of classical Be stars, both ES and BJ polarization features, could merely be artifacts of this background emission. Such polarization signatures are only produced when the ES optical depth is $\sim 1.0$, i.e., that present in the innermost disk region of classical Be stars. The density of any coincident diffuse $H\alpha$ nebulosity present around candidate Be stars is vastly insufficient to create such a polarization signature. Thus, while some of the “Be star” detections made by $H\alpha$ spectroscopic surveys (Mazzali et al. 1996) have been shown to be spurious detections due to the presence of coincident gas (Keller & Bessell 1998), such diffuse nebulosity cannot be responsible for creating the polarimetric signals found in our data set.

5.3.3. Near-IR Colors

Further insight into the evolutionary status of candidate Be stars in our very young ($5–8$ Myr) clusters may be elicited via inspection of their near-IR colors. It has been shown that the fundamentally different composition of classical Be disks (gas) and Herbig Ae/Be disks (gas and dust) will generally result in these objects occupying distinctly different locations in $J – H$ versus $H – K$ near-IR two-color diagrams (Lada & Adams 1992; Li et al. 1994), although minor instances of overlap are observed. As such, we cross-correlated all photometrically identified candidate Be stars residing in clusters studied in this paper with the 2MASS (Skrutskie et al. 2006) survey. Targets for which we were able to extract full $JHK$ photometric data are listed in Table 13.

We plot the 2MASS $JHK$ photometry of all available sources as a function of our polarimetric classifications in Figures 15 (with...
Our type 1 sources that exhibit polarimetric BJs are plotted as red circles, our type 2 sources that exhibit ES polarimetric signatures are plotted as green triangles, and all other candidate Be stars (other type 2 sources, type 3 sources, type 4 sources, and polarimetric nondetections) are plotted as blue squares. For reference, we have also plotted the near-IR colors of 101 known Galactic Be stars tabulated by Dougherty et al. (1991) as filled black triangles, 21 LMC EROS LMC Herbig Ae/Be (HAeBe) candidate (ELHC) stars, which de Wit et al. (2005) suggest are likely to be classical Be stars, as yellow open triangles, 2MASS and ground-based (Gummersbach et al. 1995) colors of 13 Magellanic Cloud B[e] stars known to have dusty disks as light blue crosses, and the star ELHC-7, which de Wit et al. (2005) suggest is likely to be a LMC Herbig Ae/Be dusty star-disk system, as a pink triangle.

Figures 15 and 16 clearly demonstrate that most of the candidate Be stars that we were able to correlate with the 2MASS catalog do lie in a distinctly different region of the JHK two-color diagram than that occupied by known duster (Herbig Ae/Be or B[e]) systems. Furthermore, although the Magellanic Cloud candidate Be stars’ colors exhibit a wide dispersion, likely due in part to the considerable photometric errors of these faint sources (Fig. 15; Table 13), we find no clear distinction among the near-IR colors of our candidate Be stars as a function of their polarimetric classification. A small number of candidate Be stars marginally overlap with the location of duster B[e] sources, although these sources are within 3σ of the mean locus of classical Be colors. Clearly, better quality near-IR photometry of these sources should be pursued to better elucidate their evolutionary status. Two candidate Be stars clearly exhibit near-IR colors consistent with dusty disk systems, NGC 346:KWBBe 200 and NGC 456:WBBe 7. NGC 346:KWBBe 200 was not detected in our polarimetric survey owing to contamination from a nearby source; however, Wisniewski et al. (2007b) has recently published optical spectroscopic, near-IR photometric, and IR photometric observations of the target and concluded that it is a B[e] supergiant, not a classical Be star. NGC 456:WBBe 7 was observed in our polarimetric survey and assigned a classification of type 3.5. Although noisy, our intrinsic polarization data exhibited marginal evidence of a position angle rotation, which could be indicative of a dusty envelope. The star’s near-IR colors seem to verify this tentative interpretation.

For comparison, in Figure 17 we also plotted the same near-IR colors for only candidate Be stars residing in our very young (5–8 Myr) clusters. Comparison of Figures 16 and 17 reveals no distinctive differences; rather, it is quite clear that the vast majority of candidate Be stars in these very young clusters have near-IR colors consistent with those expected from classical Be stars and not pre-main-sequence Herbig Be stars. Instead, the data presented in this figure and Fig. 16 exhibit similar properties. Regardless of polarimetric classification type, all candidate Be stars in clusters of age 5–8 Myr appear consistent with the expected colors of classical Be stars and inconsistent with the observed colors of composite gas-plus-dust systems (i.e., Herbig Ae/Be, B[e] stars). We interpret these data as additional evidence that many of the photometrically identified candidate Be stars in clusters 5–8 Myr old by WB06 are classical Be stars and not pre-main-sequence Herbig Be stars.

### 5.3.4. Natal Disk Clearing Time

The clearing timescale of natal star formation material (gas and dust) will influence whether it is possible or likely, a priori, to observe early-type Herbig star-disk systems in clusters of age 5–8 Myr. Among the less massive Herbig Ae and T Tauri stars, the median lifetime of inner optically thick accretion disks is 2–3 Myr, and although exceptions do exist, there is little to no H- and K-band evidence of primordial disks beyond a median stellar age of 5 Myr (Hillenbrand 2005). The typical natal disk dissipation for more massive stars is less well known. From a detailed study of the young cluster NGC 6611, de Winter et al. (1997) suggested that the clearing of natal disk material around the more massive stars in this cluster was typically 0.1 Myr or less. Similarly, Pogodin et al. (2006) recently suggested that B0e star HD 53367 is a classical Be star, based in part on an observed episodic loss of its disk material, a phenomenon known
to characterize many classical Be stars (Porter & Rivinius 2003). Pogodin et al. (2006) also identified a 4–5 $M_\odot$ pre-main-sequence binary companion which, given the pre-main-sequence evolutionary tracks of Palla & Stahler (1993), suggests that the system’s age is <0.8 Myr and indicates that the natal gas-plus-dust disk of the B0e star HD 53367 must have dissipated at least on this timescale. Although clearly not conclusive, these results do suggest that it is reasonable to expect that most of the natal disks will have been cleared from the early B-type stars in our clusters of age 5–8 Myr.

5.3.5. Summary: Most Candidate Be Stars in Clusters 5–8 Myr Old Are Classical Be Stars

WB06 and Keller et al. (1999) identified a large population of B-type stars in clusters of age 5–8 Myr that exhibited an excess of Hα emission. Observational studies suggest that the natal star formation disks of early B-type stars can clear on timescales of at least 0.1–0.8 Myr, although it is admittedly not clear if this timescale is “typical” for all early-type B stars. The near-IR colors of many of the excess Hα emitters in these very young clusters are consistent with those expected from gaseous classical Be stars and generally inconsistent with those observed from dustier B[e] and/or Herbig Ae/Be disk systems. The observed wavelength dependence of intrinsic polarization of many Hα excess stars in clusters of age 5–8 Myr is also consistent with that expected from pure gas disk systems (classical Be stars) and exhibits no evidence of secondary contributions from dust scattering, as would be expected for composite disk systems (Herbig Ae/Be, B[e] stars). Based on these factors, we suggest that there is compelling evidence supporting the existence of classical Be stars in clusters of age 5–8 Myr.

5.3.6. Be Stars in the First Half of a B Star’s Main-Sequence Lifetime: A Comparison to Fabregat & Torrejón (2000) and Martayan et al. (2007)

As outlined and summarized in § 5.3.5, data presented in this paper support the suggestion of WB06 that classical Be stars do develop before the midpoint main-sequence lifetime of a B star. Specifically, these data support the presence of a significant number of classical Be stars, with crude photometric spectral types of B0–B5 (WB06), in clusters spanning a near-continuous range of ages from log (t) of 6.7–8.1, i.e., 5–126 Myr. These results conflict with claims made by Fabregat & Torrejón (2000) and Martayan et al. (2007) that the Be phenomenon develops in the second half of a B star’s main-sequence lifetime. Martayan et al. (2007) do suggest that massive Be stars may briefly appear near the zero-age main-sequence (ZAMS) in the SMC and LMC, before losing their “Be status,” until the very end of the first part of their main-sequence lifetimes. We note that this conclusion was essentially based on a single cluster population, which limits its robustness.

WB06 reported, and the intrinsic polarization presented in this paper supports, the detection of a large body of Magellanic Cloud Be stars, with crude, photometrically assigned spectral types of B0–B5, in clusters spanning a range of ages from 5–126 Myr. No abrupt absence of classical Be stars was observed in any of the younger type clusters of our photometric and/or polarimetric data sets. Thus, our larger, more complete investigation of Be stars in Magellanic Cloud clusters calls into question the suggestion that the Be phenomenon is primarily restricted to the second half of the main-sequence lifetime of B stars (Fabregat & Torrejón 2000; Martayan et al. 2007) and contradicts the appearance-disappearance-reappearance of the Be phenomenon suggested by Martayan et al. (2007).

5.3.7. Implications of the Presence of Be Stars in Very Young Clusters

WB06 first reported the presence of candidate classical Be stars in clusters as young as 5 Myr and noted that if such objects were truly classical Be stars, they would not have spent enough time on the main sequence to spin up to near-critical rotation velocities via the mechanism proposed by Meynet & Maeder (2000) or via mass transfer in a binary system (McSwain & Gies 2005). The confirmation of the classical Be status of many of these stars via the present study can be interpreted as evidence that a significant number of classical Be stars emerge onto the ZAMS at near critical rotation velocities. An alternate interpretation of our results is that these youthful classical Be stars are evidence of the existence of a subset of the Be phenomenon, which rotate at significantly subcritical rates, perhaps as low as 0.4–0.6$c_{\text{crit}}$ for early-type B stars (Cranmer 2005). Cranmer (2005) suggested that only a subset of early-type (O7–B2) Be stars might be subcritical rotators, while later type objects (B3–A0) should be all near-critical rotators. Our photometric survey of these very young clusters assigned crude spectral types to these candidate Be stars of B0–B5 (WB06); however, owing to detection biases in our follow-up polarimetric observations, we have in general only been able to confirm that portions of the brightest of these candidates (i.e., the earliest spectral subtypes, B0 to ~B3) are bona fide classical Be stars. Thus, our present observations do not rule out the possibility that some of our very young bona fide classical Be stars might belong to the subcritical rotation population predicted by Cranmer (2005).

The observed emergence of the Be phenomenon earlier in the main-sequence lifetime than previously thought also has important implications regarding the role of magnetic fields in the formation of Be disks (Cassinelli et al. 2002). MacGregor & Cassinelli (2003) investigated the transport of magnetic flux tubes in 9 $M_\odot$ stars (~B2.5–B3) and found that these structures could rise from the core to the surface within the (at the time) expected beginning of the Be phenomenon, the midpoint main-sequence lifetime. The present study has confirmed the presence of bona fide classical Be stars in clusters as young as 5 Myr, with crude, photometrically assigned spectral types of B0 to ~B3. Although WB06 suggested the presence of an additional population of B4–B5 type candidate Be stars in these clusters, the limited dynamical range probed by the present study made it impossible to confirm the status of these fainter candidates. Although the magnetic flux transport model of MacGregor & Cassinelli (2003) had sufficient time to transport flux to the stellar surface for ~B3 stars, this is unlikely to be the case for later type stars (~B4), which have a much thicker radiative envelope. Hence, the existence of such later type Be stars in extremely young clusters would likely require an additional mechanism to be employed to accelerate the rise times of magnetic flux (J. Cassinelli 2006, personal communication). While challenging, follow-up spectroscopy of these young cluster populations would provide one avenue confirm the presence of these purported (Wisniewski & Bjorkman 2006) later type systems.

5.4. Future Work

While the present study provides significant advances in identifying and understanding the biases present in earlier 2-CD studies of cluster populations, additional work is clearly required. Our polarimetric survey was not sensitive to pole-on or near–pole-on systems; hence, determining which of our “type 2” objects are near–pole-on classical Be stars and which are astrophysical objects of a fundamentally different nature is a high priority. We suggest that follow-up moderate resolution optical spectroscopic
or infrared photometric observations would provide reasonable
diagonostics to resolve this bias and enable more quantitative
determinations of the bona fide classical Be content of clusters as a
function of age and/or metallicity. Our data suggest that at least
25% of photometrically identified candidate Be stars appear un-
likely to be true classical Be stars; however, we are unable to place
firm constraints on the true astrophysical nature of such objects.
We suggest that follow-up infrared photometric and/or spectro-
scopic observations would be useful to further constrain the evo-
lutionary nature of these objects. Furthermore, such observations
would also be useful to ascertain the true nature of candidate Be
stars that were too faint to be reliably probed by our polarimetric
observations.

Our analysis of the intrinsic polarization properties of LMC
and SMC classical Be stars suggests that the fundamental disk
properties of classical Be stars may depend on metallicity. Mod-
eling follow-up moderate-resolution spectropolarimetric obser-
vations of LMC/SMC classical Be stars is a clear avenue one
could use to further investigate these results, and we note that the
advent of accurate linear spectropolarimeters on large aperture
telescopes (i.e., the Focal Reducer Spectrograph [FORS] at the
Very Large Telescope [VLT] or the Robert Stobie Spectrograph
at the South African Large Telescope [SALT]) make obtaining
such observations feasible.

6. SUMMARY

We have used imaging polarimetric observations of six LMC
and six SMC clusters to investigate the evolutionary status of
B-type stars identified as excess Hα emitters via optical two-color
 diagram photometric techniques. We characterized the interstellar
polarization components of these data in a systematic manner, al-
lowing us to isolate the intrinsic polarization properties of our data
and hence constrain the dominant polaricgenic agent in each sys-
tem. We found:

1. The interstellar polarization associated with NGC 330 was
characterized by λ max ~ 4500 Å, suggesting the presence of a
small dust grain population.

2. The ISP of NGC 2100 exhibited clear evidence of a com-
plex morphology, indicating the presence of a nonuniform mag-
fnet field. We offer a detailed discussion of this B field and its
potential origin in Wisniewski et al. (2007a).

3. The UBVRI wavelength dependence of intrinsic polariza-
tion of many candidate Be stars in clusters of age 5–8 Myr ex-
hibit either polarization Balmer jumps and/or electron scattering
signatures, which is the expected diagnostic of free-free scatter-
ing from a gaseous disk. No evidence of a secondary polaricgenic
agent, i.e., dust scattering, is observed in these systems. More-
over, the 2MASS near-IR colors of many of these systems are
most consistent with the expected colors of pure gas disks and
inconsistent with the observed colors of dustier Magellanic Cloud
disk systems (Herbig Ae/Be, B[e]). We conclude that these data
confirm the initial suggestion of Wisniewski & Bjorkman (2006),
that classical Be stars are present in clusters of age 5–8 Myr,
contradicting claims that the Be phenomenon only develops in the
second half of a B star’s main-sequence lifetime (Fabregat &
Torresen 2000; Martayan et al. 2007), i.e., after 10 Myr.

4. We interpret the observed presence of classical Be stars in
clusters of age 5–8 Myr as evidence that a significant population
of early-type B stars must emerge onto the ZAMS rotating at
near critical velocities. We note, however, that these results do
not exclude the possibility that we are observing the hypothesized
subset of classical Be stars that rotate at subcritical velocities
(Cranmer 2005).

5. Comparing the polarimetric properties of our data set to a
similar survey of Galactic classical Be stars, we find that the pre-
vallence of polarimetric BJ signatures decreases with metallicity.
We speculate that these results might indicate that either it is more
difficult to form large disk systems in low-metallicity environ-
ments or the average disk temperature is higher in these low-
metallicity environments.

6. We find evidence that at least 25% of photometrically iden-
tified candidate Be stars do not exhibit polarimetric signatures
consistent with those expected from classical Be stars. These data
strongly suggest that caution must be exercised when attempt-
ing to correlate the onset of the Be phenomenon with evolutionary age
and/or metallicity based solely on statistics derived from simple
two-color diagram photometry.

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