EFFECTS OF METALLICITY ON THE ROTATIONAL VELOCITIES OF MASSIVE STARS

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Received 2004 July 2; accepted 2004 September 1

ABSTRACT

Recent theoretical predictions for low-metallicity massive stars predict that these stars should have drastically reduced equatorial winds (mass loss) while on the main sequence, and so should retain most of their angular momentum. Observations of both the Be/(B + Be) ratio and the blue-to-red supergiant ratio appear to have a metallicity dependence that may be caused by high rotational velocities. We have analyzed 39 archival Hubble Space Telescope Imaging Spectrograph (STIS), high-resolution, ultraviolet spectra of O-type stars in the Magellanic Clouds to determine their projected rotational velocities $V\sin i$. Our methodology is based on a previous study of the projected rotational velocities of Galactic O-type stars using International Ultraviolet Explorer (IUE) short-wavelength prime (SWP) camera high-dispersion spectra, which resulted in a catalog of $V\sin i$ values for 177 O-type stars. Here we present complementary $V\sin i$ values for 21 Large Magellanic Cloud and 22 Small Magellanic Cloud O-type stars based on STIS and IUE UV spectroscopy. The distribution of $V\sin i$ values for O-type stars in the Magellanic Clouds is compared to that of Galactic O-type stars. Despite the theoretical predictions and indirect observational evidence for high rotation, the O-type stars in the Magellanic Clouds do not appear to rotate faster than their Galactic counterparts.

Subject headings: Magellanic Clouds — stars: early-type — stars: rotation — ultraviolet: stars

1. INTRODUCTION

What effect does metallicity have on the mass loss and angular momentum loss of massive stars? There is a large amount of secondary evidence, some of which is summarized below, suggesting that low metallicity should result in less angular momentum loss, and subsequently higher rotational velocities for this type of star. However, there is an unfortunate lack of direct measurements of the equatorial rotational velocity $V_{\text{rot}}$, or even of the projected rotational velocity $V\sin i$, for massive stars in a low-$Z$ environment. The Large and Small Magellanic Clouds (LMC and SMC) are nearby, contain many young massive objects, and have low $Z$-values of 0.007 and 0.004, respectively. As such, they present an ideal laboratory to test the dependence of massive star rotation on metallicity.

Maeder et al. (1999) found a significant increase in the number ratio of Be/(B + Be) stars with decreasing metallicity among Galactic and MC clusters (see, however, the counter-arguments presented by Keller et al. 1999). The Be phenomenon is closely linked to rapid rotation (Porter & Rivinius 2003). To explain this trend in Be star number ratio, the authors raise the possibility that stars forming in a low-metallicity environment would have higher initial rotational velocities. Although no numerical models of the formation of massive stars at low $Z$ have been produced, the authors tentatively present some possible origins of these higher initial rotational velocities. A lower $Z$ environment would have a lower dust content and fewer metallic ions present in star-forming regions so that the magnetic field of the contracting central mass would be less coupled to the surrounding region. In addition, the lifetime of the accretion disk is likely related to its opacity, which would decrease with lower metallicity. These factors would result in less angular momentum loss during star formation, leading to higher initial rotational velocities. The possibility of faster initial rotation at low metallicity resulting in more rotational mixing on the main sequence has also been suggested to resolve the nitrogen enrichment seen in SMC B and A supergiants (Venn et al. 1998). Maeder et al. (1999) state, “Of course, direct observations of $V\sin i$ in LMC and SMC clusters are very much needed in order to substantiate the above results.”

Observations of the number ratio of blue to red supergiants in nearby galaxies also show a sharp dependence on metallicity (Humphreys & McElroy 1984). Stellar interior models that include rotation can account for this long-standing problem (Maeder & Meynet 2001). The primary cause of this is the mild mixing just outside the core of a rotating star during the main sequence. This increases the amount of helium near and above the H shell. The net effect of the larger He core and the mild main-sequence—mixing is to decrease the importance of the convective zone above the H-burning shell in the post—main-sequence evolution. Because of the small polytropic index in the convective zone, the larger the size of the zone, the smaller the radius of the star. Conversely, if its contribution is small, the overall size of the star increases, leading to a redward position in the Hertzsprung-Russell (HR) diagram.

Another key prediction of these new models is shown by comparing Figure 10 of Meynet & Maeder (2000) and Figure 3 of Maeder & Meynet (2001). These are plots of the evolution of surface rotational velocities for massive stars in both Galactic and SMC metallicity, respectively. At low $Z$, the surface rotational velocities will remain almost constant during the main-sequence evolution, contrary to that of massive stars at...
solar metallicity in which the rotational velocities are predicted to rapidly decrease. Theoretically, this results from both lower equatorial mass loss and the outward transport of angular momentum from the interior of the star by meridional circulation. Models of massive stars at both metallicities show a drastic decrease in rotational velocity after the terminal-age main sequence.

The idea that a low-metallicity environment would create massive, rapidly rotating helium stars has even been raised by theorists as a possible source of gamma-ray burst progenitors (MacFadyen & Woosley 1999). Here the outer layers of the star and, in at least some cases, the mantle have too much angular momentum to fall freely inside the last stable orbit during core collapse. An accretion disk forms where the dissipation of rotational and gravitational energy will give rise to some sort of mass ejection and electromagnetic radiation, a “hypernova.” This results in the prompt formation of a black hole through hyperaccretion.

2. PROJECTED ROTATIONAL VELOCITIES FROM UV LINES

Stellar rotation is the dominant process in shaping the photospheric lines of O-type stars. The vast number of lines present in the ultraviolet spectra of O-type stars suggests that accurate projected rotational velocities could be found by studying these objects in the ultraviolet. These lines arise from high excitation transitions from deeper in the photosphere, and they are less subject to wind variability than optical lines. In addition, they are less likely to be contaminated by weak emission from circumstellar and nebular gas. The standard method of individual profile fitting in the UV is difficult because of line blending. A powerful alternative involves cross-correlation of a narrow-lined star with a test star, which results in a cross-correlation function (ccf) that represents a “superline” of the test star. This technique actually increases the S/N of the observed spectrum by in effect combining all the UV lines into one. The “superline” has an observed width related to the line width of the test star and that of the narrow-lined star (Fig. 1). Fitting this “superline” is the numerical equivalent of fitting each UV absorption feature and combining the resulting measurements. Our previously derived $V \sin i$ values for 177 Galactic O-type stars were calculated by calibrating the widths of ccf’s derived from International Ultraviolet Explorer (IUE) short-wavelength prime (SWP) high-dispersion spectra as a function of published $V \sin i$ values from Conti & Ebbets (1977) in a common sample of objects (Penny 1996, hereafter P96). Conti & Ebbets (1977) fit artificially broadened model line profiles (from the non-LTE model atmospheres of Auer & Mihalas 1972) of four visual absorption line transitions.
those from our study. The technique differed slightly from ours, their findings supported the 373 OB-type stars using the high-resolution spectra of the IUE instrument, with an effective spectral resolving power of 1150–1700 km s\(^{-1}\). Although their calibration technique differed slightly from ours, their findings supported those from our study.

3. OBSERVATIONS AND REDUCTIONS

Methods similar to those above can be used with observations of O-type stars made with the Space Telescope Imaging Spectrograph (STIS) E140M grating. The E140M grating produces in a single exposure an echelle spectrogram covering the wavelength interval 1150–1700 Å, with an effective spectral resolving power of \( R = 46,000 \). This grating setup is complementary to the IUE SWP arrangement that was used so effectively to obtain an almost complete catalog of UV observations of Galactic O-type stars to \( V \approx 1 \). The Multimission Archive at Space Telescope (MAST\(^1\)) contains spectra of the 18 SMC and 6 LMC O-type stars observed with this grating. We note that the 18 STIS SMC observations were obtained through GO 7437. These may have a bias toward small projected rotational velocities. There are also STIS E140M grating archival spectra of 12 Galactic O-type stars, which we obtained in order to calibrate our methodology with the STIS observations. Although the E140M spectra are similar in many ways to the SWP high-resolution spectra in our previous methodology, it is prudent to use these overlapping Galactic stars as experimental checks of our calibration. There are also available in MAST IUE SWP high-resolution spectra of 4 SMC and 16 LMC O-type stars; one of the latter is among those with archival STIS spectra.

The NEWSIPS MXHI files of the above SWP spectra are spectrograms that cover the wavelength region of 1200–1900 Å. The archival STIS spectra are in extracted one-dimensional FITS format, forming a near-complete spectrogram covering the wavelength range 1150–1700 Å. We use a series of routines that we have written in the Interactive Data Language\(^2\) to further reduce the spectra (see details in Penny et al. 1997). One of the most important steps in our reduction is the placement of the data on a log \( \lambda \) grid, in which each pixel step corresponds to a uniform velocity step of 1 pixel = \( 10 \) km s\(^{-1}\). The spectra were smoothed using a Gaussian transfer function (FWHM = \( 40 \) km s\(^{-1}\)), and the interstellar features were removed. The spectra were then rectified to a unit continuum.

Complete lists of spectra obtained, targets, and their spectral classifications are presented in Tables 1, 2, and 3 for Galactic, SMC, and LMC targets, respectively. Spectral classifications given with square brackets are from investigators other than Walborn (see Maíz-Apellániz et al. 2004) and are taken from the compilations of Howarth & Prinja (1989), Conti & Ebbets (1977), Garmany et al. (1987, 1994), Conti et al. (1986), Parker et al. (1992), and Massey et al. (1989a, 1989b, 1995). We make special note of the SMC star AV 423. This star is classified as O9.5 II(n) by Walborn et al. (2002). Its UV spectrum is plotted in Figure 2. Both Si iv \( \lambda 1400 \) and C iv \( \lambda 1550 \) doublets have P Cygni profiles, which makes this one of the only stars known in the SMC with Si iv emission. This feature in SMC is indicative of a supergiant classification. However, the N iv doublet is extremely weak even in absorption. In addition to AV 423, we also plot AV 15 [O6.5 II(f)], AV 83 [O7 Iaf+], and NGC 346–12 [O9.5–B0 V] for comparison in Figure 2.

4. PROJECTED ROTATIONAL VELOCITIES FROM CROSS-CORRELATION FUNCTIONS

The spectra for each star are cross-correlated with a narrow-lined template star. We actually cross-correlate each test star with four different templates in order to get the best (usually highest) peak for fitting. These templates are HD 34078 (O9.5 V, \( V sin i = 25 \) km s\(^{-1}\)), HD 149438 (B0.2 IV, \( V sin i < 5 \) km s\(^{-1}\)), HD 54662 (O6.5 V, \( V sin i = 85 \) km s\(^{-1}\)), and HD 57682 (O9 IV, \( V sin i = 33 \) km s\(^{-1}\)). We cross-correlate essentially the full wavelength range of the spectra (STIS: 1200–1700 Å; IUE: 1200–1900 Å), setting to unity regions surrounding the strong P Cygni lines of N v \( \lambda 1240 \), Si iv \( \lambda 1400 \), and C iv \( \lambda 1550 \), since these features reflect wind and not photospheric rotational motion. The region around Ly\( \alpha \) is also set to unity. The spectra are padded with 1000 km s\(^{-1}\) of artificial continuum on both ends to include the entire observed range in the cross-correlation. The cross-correlation function (ccf) is the sum of the square of the differences between the test spectrum and the reference spectrum shifted in velocity from \(-1000 \) km s\(^{-1}\) to \(+1000 \) km s\(^{-1}\) at 10 km s\(^{-1}\) intervals. The ccf’s are rectified and inverted for convenience in fitting and plotting. Each ccf is then fitted with a Gaussian

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1 Available at [http://archive.stsci.edu/](http://archive.stsci.edu/).

2 IDL is a registered trademark of Research Systems, Inc.
function, and $V \sin i$ values are derived from the Gaussian widths using the calibrations presented in P96 (HD 34078), Penny et al. (2001, HD 149438), Penny et al. (1997, HD 54662), and Penny (1997, HD 57682). We adopt 40 km s$^{-1}$ as our minimum measurable $V \sin i$, as this is the FWHM of the Gaussian transfer function used to smooth the data.

We compared $V \sin i$ values from our previous study to those obtained using STIS observations for those Galactic O-type stars in common. This is especially important since the wavelength range in the STIS spectra is smaller than that of the $IUE$ observations, which might introduce systematic differences in our $V \sin i$ values. We plot in Figure 3 $V \sin i$ values from the STIS observations versus those from the $IUE$ observations. We see excellent agreement, well within our estimated errors from the $IUE$ data ($\pm 2\%-5\%$), with the exception of HD 13745. This star is noted in P96 as being a possible unresolved double-lined.

**TABLE 2**

| Star     | Spectral Classification | $V \sin i$ (km s$^{-1}$) | SWP No. or STIS Data Set |
|----------|-------------------------|--------------------------|--------------------------|
| NGC 346−355... | O2 III(f*)             | 112                      | 120                      | O4WR01010 |
| AV 388... | [O4 V]                  | 179                      | ...                      | SWP33968  |
| NGC 346−324... | O4 V(f)               | 70                       | 120                      | O4WR01020 |
| NGC 346−368... | O4−5 V(f(f))          | 55                       | 80                       | O4WR01030 |
| AV 80... | O4−6 n(f)               | 324                      | 270                      | O4WR12010, 12020 |
| AV 75... | O5 III(f+)              | 109                      | 110                      | O4WR11010, 11020 |
| NGC 346−113... | OC6 Vz                 | <40                      | 45                       | O4WR02010 |
| AV 243... | [O6 III]                | 62                       | ...                      | SWP33961  |
| NGC 346−487... | [O6.5 V]               | 65                       | ...                      | O4WR23010 |
| AV 15... | O6.5 II(f)              | 128                      | 132                      | O4WR14010, 14020 |
| AV 220... | O6.5f?p                 | <40                      | 62                       | O4WR20010, 20020 |
| Sk 80... | [O6.5 II]               | 106                      | ...                      | SWP05654, 25438 |
| AV 95... | O7 III(f)               | 82                       | 89                       | O4WR17010, 17020 |
| AV 26... | [O7 III]                | 127                      | ...                      | SWP32466  |
| AV 83... | O7 Iaf+                 | 82                       | 80                       | O4WR15010, 15020 |
| AV 69... | O7.5 III(f(f))         | 100                      | 104                      | O4WR13010, 13020 |
| NGC 346−682... | [O8 V]                | 71                       | ...                      | O4WR24010 |
| AV 47... | O8 III(f)               | 76                       | 169                      | O4WR16010, 16020 |
| AV 423... | O9.5 II(n)             | 186                      | ...                      | O4WR18010, 18020 |
| NGC 346−12... | O9.5−B0 V              | 67                       | 84                       | O4WR21010 |
| AV 327... | O9.5 II−Ibw             | 71                       | 80                       | O4WR30010, 30020 |
| AV 170... | O9.7 III                | 54                       | 65                       | O4WR18010, 18020 |

**TABLE 3**

| Star     | Spectral Classification | $V \sin i$ (km s$^{-1}$) | SWP No. or STIS Data Set |
|----------|-------------------------|--------------------------|--------------------------|
| HD 269810... | O2 III(f*)             | 173                      | O6LZ11010 |
| SK −66 172... | O2 III(F*)+OB         | 68                       | SWP33971  |
| HD 269698... | O4 I                   | 157                      | 60697       |
| HD 269676... | O4−5 III(f)           | 128                      | O63541010 |
| HD 269676... | O4−5 III(f)           | 156                      | SWP05806, 13908, 14022 |
| SK −69 212... | [O5 III(f)]           | 210                      | SWP52709   |
| LH 10−3120... | [O5.5 V(f*)]          | 95                       | O5EZ01010, 01020, 01030 |
| SK −66 100... | [O6 III]              | 116                      | SWP33139   |
| HD 270952... | O6 Iaf                 | 61                       | SWP45216   |
| HD 269357... | O6 I                   | 97                       | SWP04314, 55231 |
| SK −67 111... | [O6 Iaf(n)]           | 209                      | SWP10991, 52745 |
| SK −67 51... | [O6.5 III]             | 105                      | SWP31341   |
| CD −68 264... | [O8 V]                | 139                      | SWP47851   |
| SK −67 101... | [O8 III(f)]           | 101                      | O4YN01010, 01020 |
| LH 58 52a... | [O8 III]              | 110                      | SWP49323   |
| SK −67 266... | [O8 Iaf]              | 144                      | SWP20411   |
| LH 58 19a... | [O9 II]               | 178                      | SWP49312   |
| HD 268605... | O9.7 Ibf               | 90                       | SWP06540, 51851, 52010 |
| HD 269889... | O9.7 Ibf               | 72                       | SWP47601   |
| HD 269896... | ON9.7 Ia               | 70                       | SWP47594, 52516 |
| SK −67 106... | [B0 III]              | 135                      | O4YN03010  |
| SK −67 107... | [B0 III]              | 103                      | O4YN04010, 04020 |
spectroscopic binary, or it may be a short period pulsator (Koen & Eyer 2002), so a larger than expected difference in $V \sin i$ here is not unexpected.

Our calculated projected rotational velocities are presented in Tables 2 and 3. Previous estimates of $V \sin i$ for the SMC stars in common by Walborn et al. (2000, in the table W00) are also shown in Table 2. We note that they describe their values as preliminary because of the blended nature of the He I + He II $\lambda 4026$ line from which their estimates are determined. Nevertheless, there is reasonable agreement between our results, except in the cases of NGC 346--324 and AV 47, which may be spectroscopic binaries observed at differing orbital phases. The SMC contains both the slowest and fastest rotators among our sample of Magellanic Cloud stars. Both NGC 346--113 and AV 220 have narrow-lined spectra, indicating a $V \sin i$ below the minimum for which we can determine an accurate projected rotational velocity ($< 40$ km s$^{-1}$). The fastest rotator is AV 80, which has a $V \sin i$ comparable to that found in some Be stars. Walborn et al. (2000) show that the He II $\lambda 4686$ feature is a double-peaked emission line in this star, which suggests that this star may have a disklike circumstellar envelope, again like those found in Be stars.

5. RESULTS AND CONCLUSIONS

While our ultimate goal is to determine the true rotational velocities of O-type stars in differing environments, in general only the projected rotational velocities are measurable. However, we can make some statistical arguments. The inclination angles of the polar axes $i$ of a group of stars should be randomly distributed. For each metallicity environment (Galactic, LMC, and SMC) we expect that the distribution of $i$ should be the same, that is, random. Thus, we can safely intercompare the rotational properties through an examination of their projected rotational velocities. We can compare the projected rotational velocity distributions of the different groups of stars by calculating their cumulative distribution function (cdf), as shown in Howarth et al. (1997) and Howarth & Smith (2001). The cdf gives the fraction of stars having a $V \sin i$ less than a specific upper value that ranges from zero to the maximum $V \sin i$ observed.
Before comparing the MC samples it is helpful to determine if the cdf of Galactic dwarf (IV–V) stars is different from that of Galactic evolved (I–III) stars. We plot in Figure 4 the cdf for both groups of stars based on the sample in P96. We see that the evolved sample has both fewer slow rotators and fewer fast rotators compared to the unevolved sample. The Kolmogorov-Smirnov (K-S) test determines the probability that two samples are drawn from the same parent population. For the Galactic evolved and unevolved stars this probability is only 16%, which suggests that the differences may be significant. Howarth et al. (1997) came to the same conclusion in their study of projected rotational velocities of Galactic O-type stars. They suggest that the evolved stars do indeed spin down as they grow in radius (removing the fastest rotators from the sample), and that there exists excess turbulent broadening among the supergiants (which removes the most narrow-lined stars from the sample).

The differences in the distributions of projected rotational velocity between the unevolved and evolved groups appears to support theoretical models that predict a spin-down during the core H-burning phases of evolution (Heger & Langer 2000; Meynet & Maeder 2000). It is important to recognize that most stars with an O spectral type are probably found in the core H-burning phase, even among the more luminous stars (see the evolutionary tracks of Schaller et al. 1992). Thus, we expect that the low-Z, Magellanic Cloud O-type stars are also in this phase in which the rotational spin-down is predicted to be much less effective than we find in the Galactic sample (Maeder & Meynet 2001). The low-Z stars should retain an almost constant $V_{\text{rot}}$ during their core H-burning evolution. Therefore, we expected that the cumulative distribution function for the low-Z stars would fall well below that of Galactic stars because of the relative excess of rapid rotators.

The existence of a systematic difference between the velocity distributions of Galactic unevolved and evolved O-type stars (Fig. 4) indicates that we must compare like samples between the Galactic and Magellanic Cloud stars in order to avoid spurious results because of differing proportions of unevolved and evolved stars in the groups. A large percentage of our Magellanic Cloud samples are objects with evolved luminosity classes (68% and 90% for the SMC and LMC samples, respectively). Note that we include the two SMC stars lacking a luminosity class, AV 80 and AV 220, among the evolved stars since Walborn et al. (2000) find them to have luminosities consistent with an advanced evolutionary state. We also include SMC star AV 423 among the evolved group because of the features in the UV spectrum indicating a high luminosity (see §3). We show in Figure 5 the cumulative distribution functions for the evolved O-type stars in the Galaxy, SMC, and LMC. Surprisingly, the distributions for all three samples are very similar, with K-S probabilities of 44% and 42% that the LMC and SMC samples, respectively, are drawn from the same parent population as the Galactic sample. There is no visible trend of cumulative distribution functions with metallicity. The LMC sample has slightly faster $V\sin i$ values than that of the Galactic stars, but the SMC objects have slightly slower rotation rates than the other two samples. There are too few unevolved stars to make a reliable comparison, but the average projected rotational velocities in each group appear to be comparable: $\langle V\sin i \rangle = 131 \pm 93$, $117 \pm 31$, and $78 \pm 45$ km s$^{-1}$ for the Galactic, LMC, and SMC unevolved stars, respectively.

Taken at face value, our results do not support the prediction that the low-Z stars of the Magellanic Clouds are rapid rotators. However, because of our relatively small sample sizes, we clearly need additional measurements to confirm the result. Are low-Z stars actually rotating at the same speeds as their Galactic counterparts? In order to determine conclusively the answer, a larger number of $V\sin i$ values for stars in these environments is needed. A previous study by Keller (2001) examined the rotation rates of 100 early B-type stars in the LMC. Compared with a similar sample of Galactic stars, the low-metallicity stars show larger rotation rates. The largest initial mass of these early B-type stars is only 12 $M_\odot$, and as such their main-sequence evolution is not expected to be influenced by mass loss. However, this is exactly the sort of large-scale project that is necessary for the more massive O-type stars. A project with the FLAMES multi-object spectrograph on the VLT to obtain such spectra is currently ongoing. In addition, efforts are underway that focus on observing evolved (I–III classes) early type (O3–O5) stars in the LMC. As these stars should correspond to a later stage in the core H-burning evolution of the most massive stars, they represent a critical test of the current treatment of mass and angular momentum loss in low-metallicity massive stars.

![Figure 4](image1.png)  
**Fig. 4.—Cumulative distributions of projected rotational velocities for Galactic stars from Penny (1996). The dotted line represents those objects with luminosity classes IV and V, while the solid line corresponds to stars with luminosity classes I, II, and III.**

![Figure 5](image2.png)  
**Fig. 5.—Cumulative distribution of projected rotational velocities for 15 SMC (dotted line), 19 LMC (dashed line), and 95 Galactic (solid line) O-type stars of luminosity class I–III.**
Support for this project AR No. 09945 was provided in part by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. The data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NAG 5-7584 and by other grants and contracts.

REFERENCES

Auer, L. H., & Mihalas, D. 1972, ApJS, 24, 193
Conti, P. S., & Ebbets, D. 1977, ApJ, 213, 438
Conti, P. S., Garmany, C. D., & Massey, P. 1986, AJ, 92, 48
Garmany, C. D., Conti, P. S., & Massey, P. 1987, AJ, 93, 1070
Garmany, C. D., Massey, P., & Parker, J. W. 1994, AJ, 108, 1256
Heger, A., & Langer, N. 2000, ApJ, 544, 1016
Howarth, I. D., & Prinja, R. K. 1989, ApJS, 69, 527
Howarth, I. D., Seibert, K. W., Hussain, A. J., & Prinja, R. K. 1997, MNRAS, 284, 265
Howarth, I. D., & Smith, K. C. 2001, MNRAS, 327, 353
Humphreys, R. M., & McElroy, D. B. 1984, ApJ, 284, 565
Keller, S. C. 2001, PASP, 113, 1570
Keller, S. C., Wood, P. R., & Bessell, M. S. 1999, A&AS, 134, 489
Koen, C., & Eyer, L. 2002, MNRAS, 331, 45
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Maeder, A., Grebel, E. K., & Mermilliod, J.-C. 1999, A&A, 346, 459
Maeder, A., & Meynet, G. 2001, A&A, 373, 555
Maíz-Apellániz, J., Walborn, N. R., Galiú, H. A., & Wei, L. H. 2004, ApJS, 151, 103
Massey, P., Lang, C. C., Degioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188
Massey, P., Parker, J. W., & Garmany, C. D. 1989a, AJ, 98, 1305
Massey, P., Silkey, M., Garmany, C. D., & Degioia-Eastwood, K. 1989b, AJ, 97, 107
Meynet, G., & Maeder, A. 2000, A&A, 361, 101
Parker, J. W., Garmany, C. D., Massey, P., & Walborn, N. 1992, AJ, 103, 1205
Penny, L. R. 1996, ApJ, 463, 737 (P96)
———. 1997, PASP, 109, 848
Penny, L. R., Gies, D. R., & Bagnuolo, W. G., Jr. 1997, ApJ, 483, 439
Penny, L. R., Scyle, D., Gies, D. R., Harvin, J. A., Bagnuolo, W. G., Jr., Thaller, M. L., Fullerton, A. W., & Kaper, L. 2001, ApJ, 548, 889
Porter, J. M., & Rivinius, T. 2003, PASP, 115, 1153
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Venn, K. A., McCarthy, J. K., Lennon, D. J., & Kudritzki, R. P. 1998, in ASP Conf. Ser. 131, Boulder-Munich II: Properties of Hot, Luminous Stars, ed. I. Howarth (San Francisco: ASP), 177
Walborn, N. R., Lennon, D. J., Heap, S. R., Lindler, D. J., Smith, L. J., Evans, C. J., & Parker, J. W. 2000, PASP, 112, 1243 (W00)
Walborn, N. R., Fullerton, A. W., Crowther, P. A., Bianchi, L., Hutchings, J. B., Pellerin, A., Sonneborn, G., & Willis, A. J. 2002, ApJS, 141, 443