THE ASTROPHYSICAL JOURNAL, 484:L153–L156, 1997 August 1

FUNDAMENTAL STELLAR PARAMETERS OF γ^2 VELORUM FROM *HIPPARCOS* DATA[1]

DANIEL SCHAERER,[2,3,4] WERNER SCHMUTZ,[5] AND MICHEL GRENON[3]
Received 1997 March 11; accepted 1997 May 22

ABSTRACT

We report parallax measurements by the *HIPPARCOS* satellite of γ^2 Velorum and a few related objects. The distance of γ^2 Vel is $d = 258^{+41}_{-31}$ pc, significantly smaller than the commonly adopted value to Vela OB2. For ζ Puppis $d = 429^{+120}_{-77}$ pc is in agreement with the canonical distance.

The total mass of γ^2 Vel derived from its parallax, the angular size of the semimajor axis as measured with intensity interferometry, and the period are M(W-R + O) = 29.5 ± 15.9 $M_{\odot}$. This result favors the orbital solution of Pike et al. over that of Moffat et al. The stellar parameters for the O star companion derived from line-blanketed non-LTE atmosphere models are $T_{\rm eff}$ = 34,000 ± 1500 K, $\log L/L_{\odot}$ = 5.3 ± 0.15, from which an evolutionary mass of M = 29 ± 4 $M_{\odot}$ and an age of $4.0^{+0.8}_{-0.5}$ Myr is obtained from single-star evolutionary models. With non-LTE model calculations including He and C, we derive a luminosity $\log L/L_{\odot} \sim 4.7 \pm 0.2$ for the W-R star. The mass-luminosity relation of hydrogen-free W-R stars implies a mass of $M_{\rm W\text{-}R} \sim 5 \pm 1.5\ M_{\odot}$.

From our data we favor an age of about 10 Myr for the bulk of the Vela OB2 stars. Evolutionary scenarios for ζ Pup and γ^2 Vel are discussed in the light of our results.

Subject headings: stars: distances — stars: early-type — stars: fundamental parameters — stars: mass loss — stars: Wolf-Rayet

1. INTRODUCTION

Accurate stellar parameters of massive stars are of fundamental importance to guide our understanding of stellar evolution. Two objects of particular interest have been associated with the Vela OB2 association: the single O star ζ Puppis [HD 66811, O4 I(n) f], used as a prototype for radiation-driven wind models (e.g., Pauldrach et al. 1994; Schaerer & Schmutz 1994 for recent models), and the closest W-R star WR 11 (HD 68273), found in the spectroscopic binary system γ^2 Velorum.

In the present Letter we discuss their fundamental stellar parameters based on distances obtained from the astrometric *HIPPARCOS* satellite. It is found that the most significant trigonometric parallax obtained by *HIPPARCOS* for W-R stars, namely, that of WR 11, is significantly larger than usually thought and also accurate enough to provide important constraints on its stellar parameters. With a 7.3 σ measurement of the parallax, γ^2 Vel also clearly stands out from the remaining four other W-R stars, which are within $2.3 \leq \sigma \leq 3.6$, as reported by van der Hucht et al. (1997). The binary nature of the γ^2 Vel system provides us with a unique opportunity to determine accurately the most important fundamental stellar parameters.

The *HIPPARCOS* data used in the present work and its accuracy are discussed in § 2. Stellar parameters for γ^2 Vel are revised and determined from non-LTE atmosphere models in §§ 3 and 4. In § 5 we discuss evolutionary scenarios for these objects in light of previous observations and new *HIPPARCOS* parallaxes of a few presumed members of the Vela OB2 and Vela R2 associations.

2. *HIPPARCOS* DATA

We have obtained *HIPPARCOS* trigonometric parallaxes from the *HIPPARCOS* Catalogue (European Space Agency 1997) for ζ Pup, γ^2 Vel, and a few related objects. The trigonometric parallaxes have been derived from a fit of an astrometric model for stellar motion with five parameters to the set of one-dimensional measurements performed in transits through the field of view between 1989 and 1993. While estimates of systematic errors in the astrometric solution are less than 0.1 mas, the external errors deviate from the standard errors quoted in the catalog by 0%–20% (Arenou et al. 1995; Lindegren 1995).

The two main objects considered in this work have significant parallaxes (4.6 σ and 7.3 σ, respectively): $\pi(\zeta$ Pup) = 2.33 ± 0.51 mas, corresponding to a distance of $d = 429^{+120}_{-77}$ pc, and $\pi(\gamma^2$ Vel) = 3.88 ± 0.53 mas, corresponding to $d = 258^{+41}_{-31}$ pc. The goodness of the *HIPPARCOS* fit indicates that the adjustment is better than the average expectation. In addition, for ζ Pup only 1% of the measurements were rejected, while for γ^2 Vel none were excluded, which shows that the parallaxes are reliable for both objects.

The *HIPPARCOS* parallax could be influenced by the orbital motion. By adopting the orbital orientation from Moffat et al. (1986), the inclination from St. Louis et al. (1987), the W-R/O star luminosity ratio from Conti & Smith (1972), and the angular size of the semimajor axis from Hanbury Brown et al. (1970), we find that the center of light is displaced by 0.3 to 1.2 mas from its average location. An interpretation of the orbital motion as a standard deviation yields 0.8 mas. For smaller magnitude differences (see below) or the orbital parameters of Pike, Stickland, & Willis (1983) this error becomes smaller. The contribution of the orbital motion to the error of the *HIPPARCOS* parallax is $0.8/\sqrt{N} = 0.09$ mas, where $N = 78$ is the number of measurements used minus the number of fitted parameters. The measured parallax of the spectroscopic binary system γ^2 Vel therefore provides an

[1] Based on data from the ESA *HIPPARCOS* astrometry satellite.
[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; schaerer@stsci.edu.
[3] Observatoire de Genève, CH-1290 Sauverny, Switzerland.
[4] Observatoire Midi-Pyrénées, Toulouse, France.
[5] Institut für Astronomie, ETH-Zentrum, CH-8092 Zürich, Switzerland.

accurate distance indicator. In the following, we shall adopt the internal *HIPPARCOS* error as the uncertainty on the parallax.

3. REVISED STELLAR PARAMETERS

3.1. ζ *Puppis*

The distance of ζ Pup as derived from the *HIPPARCOS* parallax is consistent with the canonically adopted value of $d = 450$ pc based on its presumed association with Vela OB2 (see Brandt et al. 1971), which may, however, be questionable (see § 5). Distance-dependent stellar parameters derived so far for ζ Pup are thus compatible with the *HIPPARCOS* measurement and shall not be repeated here.

3.2. γ^2 *Velorum*

Combining the *HIPPARCOS* parallax with the observed angular size of the semimajor axis from the interferometric measurements of Hanbury Brown et al. (1970) and the known orbital period (see Niemela & Sahade 1980; Pike et al. 1983) allows us to derive the total mass of the system: M(W-R + O) = 29.5 ± 15.9 $M_\odot$ (see Table 3 below for parameters).

In the recent literature, there are two different amplitudes of the orbital motion. Pike et al. (1983) derived a mass ratio of $q = 0.36 \pm 0.09$, whereas Moffat et al. (1986) find a significantly larger mass ratio of $q = 0.54 \pm 0.03$ because of a larger radial velocity amplitude for the O star. Adopting an inclination of $i = 70°$ later confirmed by St. Louis et al. (1987), Pike et al. (1983) obtain M(W-R) = 7.7 ± 2.5 $M_\odot$ and M(O) = 22 ± 5 $M_\odot$, while the Moffat et al. (1986) data yield M(W-R) = 19^{+7}_{-2} $M_\odot$ and M(O) = 35^{+13}_{-3} $M_\odot$ (see Smith & Maeder 1989). The total mass derived above using the *HIPPARCOS* parallax favors the solution of Pike et al. (1983). On the other hand, for the orbital parameters of Moffat et al. (1986) the observed angular size of the semimajor axis would imply a distance of $d = 308 \pm 37$ pc, which is within 1 σ of the *HIPPARCOS* distance. We conclude that the orbital parameters from both Pike et al. (1983) and Moffat et al. (1986) are compatible with the *HIPPARCOS* parallax and the interferometric determination of the semimajor axis from Hanbury Brown et al. (1970). The discrepancy between the two orbital solutions, however, implies a significant uncertainty for the masses of the γ^2 Vel components.

The *HIPPARCOS* distance measurement places γ^2 Vel considerably closer than the previously adopted distance ($d \sim 450$ pc) based on its assumed association with Vela OB2 (e.g., Brandt et al. 1971; Sahu 1992). The apparent magnitude and extinction from the catalog of van der Hucht et al. (1988), the flux zero-point correction of Schmutz & Vacca (1991), and the revised distance yield M_v(system) = −5.49. Absolute magnitudes obtained for the W-R and O star components, assuming different luminosity ratios, are given in Table 1. The values of $\Delta M_V = 1.4$ mag and 1.9 mag result from the comparison of equivalent widths of γ^2 Vel with those from the WC8 star WR 135 (Conti & Smith 1972; Brownsberger & Conti 1993). The absolute brightness of the WC8 star is considerably smaller than the average value for WC8 stars given by van der Hucht et al. (1988) [$\langle M_v$(WC8)$\rangle$ = −4.8].

The bolometric correction of the WC8 star can be obtained from evolutionary or atmosphere models. Adopting the mass-luminosity relation of Schaerer & Maeder (1992) or Smith, Meynet, & Mermilliod (1994), one has $\log L/L_\odot = 5.06$ (5.69) for the low (high) mass and hence a bolometric correction of BC = −4.2 to −3.7 (−5.8 to −5.3). Smith et al. (1994) derived a value of −4.5 for this subtype. From non-LTE atmosphere models (see below) we obtain BC = −3.5 to −3.4.

TABLE 1

ABSOLUTE MAGNITUDES FOR γ^2 VELORUM SYSTEM

Identification	ΔM_V	M_v(W-R)	M_V(O)
CS72	1.4	−3.83	−5.13
BC93	1.9	−3.42	−5.22
1	1.36	−3.86	−5.12
2	1.75	−3.54	−5.20

NOTE.—Derived absolute magnitudes for the γ^2 Vel system for different assumptions on the W-R − O magnitude difference. Codes in col. (1) are as follows: (CS72) Conti & Smith 1972; (BC93) Brownsberger & Conti 1993; (1, 2) models presented in Table 2. M_v(system) = −5.49, M_V (system) = −5.39, where v stands for the Smith and V the Johnson system.

The brightness of the O star is typical for a giant (see Vacca et al. 1996). Conti & Smith (1972) concluded that the O star is a supergiant, based on the ratio 4089 Si IV/4143 He I. However, they note that the measurements have been difficult because of blending effects. The fast rotation of the O star makes it indeed difficult to locate a weak He I line in a spectrum dominated by W-R features and to isolate Si IV λ4089 from a nearby nitrogen line. Therefore, the spectroscopic luminosity classification is not severely in conflict with the absolute magnitude of the O star. Comparing two spectra from Kaufer et al. (1997) observed at the phases $\phi = 0.24$ and 0.72, we find that He II λ4686 is in absorption. Its equivalent width corrected for the emission of the W-R star is compatible with a classification as a giant (Mathys 1988), especially when considering the large uncertainty of measuring a broad absorption superposed on a strong emission line.

A statistical argument against a luminosity class I can be made based on the observed rotation of $v_{rot} \sin i = 220$ km s^{-1} (Baade, Schmutz, & van Kerkwijk 1990). For a supergiant such a velocity is extremely rare, whereas for giants such high values are more ordinary (see Howarth et al. 1997). We determine a 4471 He I/4541 He II ratio of 1.6 ± 0.2. According to Mathys (1988), this classifies the O star as O8 or O8.5. Conti & Smith (1972) have determined O9 spectral type. We agree in the equivalent width for the 4471 line, but in our spectra the He II λ4541 absorption is much stronger than what is cited by Conti & Smith (1972). We therefore favor a reclassification of γ^2 Vel as WC8+O8 III.

The radio mass-loss rate of WR 11 that was recently rederived by Leitherer, Chapman, & Koribalski (1997) has to be reduced by a factor of 2.3, which yields $\log \dot{M} = -4.55 \pm 0.16$ $M_\odot$ yr^{-1}. This value is more typical of $\dot{M}$ of WC9 stars, which seem to show lower mass-loss rates than W-R stars of other types. It may, however, be underestimated if the ionization in the outer parts of the winds is lower than assumed (Leitherer et al.). Interestingly, $\dot{M}$ is now in good agreement with results from fits of *ASCA* X-ray observations with the hydrodynamic wind-collision models of Stevens et al. (1996), who obtained $\dot{M} \sim 3 \times 10^{-5}$ $M_\odot$ yr^{-1}. Agreement between both methods may weaken the requirement of important structure ("clumping") in the wind (see Stevens et al. 1996), which, if present, leads to an overestimate of the radio mass-loss rate. The degree of reliability of colliding wind models is, however, not yet well known (see Gayley, Owocki, & Cranmer 1997).

Depending on the adopted W-R mass, the mass-dependent

TABLE 2

STELLAR PARAMETERS FOR WR 11 DERIVED FROM NON-LTE ATMOSPHERE MODELS

Identification	$T_\star$ (kK)	$R_\star$ ($R_\odot$)	log $\dot{M}$ ($M_\odot$ yr^{-1})	log L ($L_\odot$)	BC (mag)	log Q_0 (s^{-1})
1	51.0	3.3	−4.2	4.8	−3.5	48.5
2	61.0	1.9	−4.3	4.7	−3.4	48.4

mass-loss rate formula of Langer (1989) for WC stars yields values between log $\dot{M} = -4.78$ and -3.80 $M_\odot$ yr^{-1}. With the recently proposed relation of Schmutz (1997), the values are log $\dot{M} = -5.32$ and -4.54 $M_\odot$ yr^{-1}. A better constraint on M is clearly necessary for an accurate test of such a relation.

A 1.8 MeV γ-ray line emission of (2.3–5) $\times 10^5$ cm^{-2} s^{-1} has been detected in the direction of the Vela supernova remnant (SNR) (Diehl et al. 1995). From the ^{26}Al yields of Meynet et al. (1997) the contribution of γ^2 Vel to the γ-ray flux is estimated to be (1.5–2.6) $\times 10^{-5}$ with our new distance measurement. This values depends, however, quite strongly on the evolutionary scenario of the W-R star, which is still uncertain (see § 5).

4. NON-LTE MODEL ANALYSIS FOR γ^2 VELORUM STARS

From a line-blanketed non-LTE analysis of the photospheric classification lines He I λ4471 and He II λ4541 of the O star we derive $T_{\rm eff}(O) = 33{,}500 \pm 1500$ K and $\log L(O)/L_\odot = 5.3 \pm 0.15$ for $M_V(O) = -5.13$.

Its Lyman continuum flux is log (Q_0) = 48.7 photons s^{-1}. From the above values we derive M(O) = 29 ± 4 $M_\odot$ and an age of about 4 ± 0.5 Myr from single-star evolutionary models (Meynet et al. 1994). With the age of the O star and the luminosity of the WC companion (see below), single-star evolutionary models yield an estimate of $M_{\rm ini} \sim 57 \pm 15$ $M_\odot$ for the initial mass of the WC8 star.

A coarse analysis of the WC stellar parameters can be obtained from a model grid following the general procedure of Schmutz, Hamann, & Wessolowski (1989). The non-LTE models used for this purpose include He and C with an abundance of C/He = 0.25 by number. The adopted terminal velocity is v_∞ = 1450 km s^{-1} (Eenens & Williams 1994). We use the observed equivalent widths of He I λ5876 and He II λ5412 [EW(5876) = 9.5 ± 2.5 Å and EW(5412) = 4 ± 1 Å] and correct these values for the contamination by the light of the companion. The analysis then yields the temperature $T_\star$, radius $R_\star$, and $\dot{M}$. From the uncertainties of the EWs and the fit procedure we estimate an internal error of about ±0.2 dex on the luminosity L. In Table 2 we list the parameters derived for the different assumptions for the magnitude difference between the components (see also Tables 1 and 3). We find that the γ^2 Vel system provides approximately a factor of six less ionizing photons than ζ Pup [log (Q_0) = 49.7 photons s^{-1}; see Schaerer & Schmutz 1994].

We have used a simpler model for carbon than the more elaborate calculations by Koesterke & Hamann (1995). Test calculations with the parameters for the WC8 star WR 135 derived by Koesterke & Hamann (1995) showed that our computations agree very accurately for the helium lines, but we found less agreement for the carbon lines. Therefore, we have used only the helium lines for the spectroscopic diagnostic. We have also performed a coarse analysis using the grid of Koesterke & Hamann (1995) for $\beta_C = 0.2$ (C/He = 0.083 by number). Although we get systematically lower temperatures,

TABLE 3

SUMMARY OF PARAMETERS FOR γ^2 VELORUM

Quantity	Value	Alternate Value	Reference
π (mas)	3.88 ± 0.53	...	1
$d = 1/\pi$ (pc)	258^{+41}_{-31}	...	1
a (mas)	4.3 ± 0.5	...	2
P (days)	78.5002 ± 0.0001	...	3
$M_{\rm tot}$	29.5 ± 15.9	...	1
K(O) (km s^{-1})	40.9 ± 6.5	70 ± 2	4, 5
q	0.36 ± 0.09	0.54 ± 0.03	4, 5
i (deg)	70 ± 10	...	6
e	0.38 ± 0.03	0.40	4, 5
M(W-R) ($M_\odot$)	7.7 ± 2.5	19^{+7}_{-2}	4, 7
M(O) ($M_\odot$)	22 ± 5	35^{+13}_{-3}	4, 7
log L(W-R)$_{M-L}$ ($L_\odot$)	5.06	5.69	1
v_∞(W-R) (km s^{-1})	1450	...	8
log $\dot{M}$(W-R) ($M_\odot$ yr^{-1})	−4.55 ± 0.16	...	1
log L(W-R)$_{\rm NLTE}$ ($L_\odot$)	~4.7–4.8	...	1
$T_{\rm eff}$(O) (K)	34,000 ± 1500	...	1
log L(O)$_{\rm NLTE}$ ($L_\odot$)	5.3 ± 0.15	...	1
M(O)$_{\rm evol}$ ($M_\odot$)	29 ± 4	...	1
Age(O) (Myr)	$4.0^{+0.8}_{-0.5}$	...	1

NOTE.—Col. (3) gives alternate values for certain parameters.

REFERENCES.— (1) this Letter; (2) Hanbury Brown et al. 1970; (3) Niemela & Sahade 1980; (4) Pike, Stickland, & Willis 1983; (5) Moffat et al. 1986; (6) St. Louis et al. 1987; (7) Smith & Maeder 1989; (8) Eenens et al. 1994.

we find that L is essentially identical. We therefore conclude that the luminosity obtained from our model is consistent with the WC models from Koesterke & Hamann (1995). The parameters $T_\star$ and $R_\star$ depend quite strongly on assumptions about the velocity law and are therefore less reliable (e.g., Schmutz 1996, 1997).

For the luminosity derived from the atmosphere models the M-L relation gives M(W-R) ~ 5 ± 1.5 $M_\odot$, which is compatible with the low mass determination for WR 11. On the other hand, if the mass is of the order of 19 $M_\odot$ (as mostly adopted in the literature), then we are faced with a serious discrepancy (up to an order of magnitude!) between L derived from atmosphere and evolutionary models. The work of Howarth & Schmutz (1992) and Schmutz (1996, 1997) previously revealed differences for some WN stars. According to Schmutz (1996, 1997), this is most likely due to systematic errors in the non-LTE model atmosphere, and it may lead to underestimates of L by typically 50% to 300%. We conclude that for the low mass determination of WR 11 the theoretical M-L relation for hydrogen-free W-R stars agrees within the errors with L derived from atmosphere models.

5. DISCUSSION

The distance and the origin of the Gum nebula, the spatial distribution of important objects in this region (Gum nebula, Vela R2 and Vela OB associations, ζ Pup, γ^2 Vel, the Vela SNR, etc.) and their possible relation are still relatively poorly known and controversial (see, e.g., Brandt et al. 1971; Bruhweiler, Kafatos, & Brandt 1983; Franco 1990; Sahu 1992; Sahu & Blaauw 1993; Oberlack et al. 1994; Fitzpatrick & Spitzer 1994; Aschenbach, Egger, & Trümper 1995). Combining recent data (including additional *HIPPARCOS* parallaxes and proper motions) with the most elaborate study of this region done by Sahu (1992) may lead to a refined picture. While such a task is clearly beyond the scope of the present Letter, we shall in the following briefly discuss a few questions related to ζ Pup and γ^2 Vel.

Based on its proper motion Sahu (1992) suggested that the runaway star ζ Pup originates from the more distant young Vela R2 association. Although the *HIPPARCOS* distance to ζ Pup is lower than the approximately 730 pc suggested by Sahu, her scenario remains valid provided the distance to Vela R2 is less than the adopted 800 pc,[6] which is compatible with the distance estimate of Liseau et al. (1992) and the *HIPPARCOS* parallax of two presumed members (HD 76534, 2.43 ± 1.30; HD 76838, 3.39 ± 0.90 mas). Evolutionary scenarios for ζ Pup have been presented by van Rensbergen, Vanbeveren, & de Loore (1996). It would be highly desirable to include the effects of the rapid rotation of ζ Pup in future calculations.

We obtained additional *HIPPARCOS* parallaxes for five presumed Vela OB2 members (HD 63922, 1.66 ± 0.53; HD 64740, 4.53 ± 0.52; HD 68657, 4.48 ± 0.49; HD 70930, 2.16 ± 0.57; HD 72485, 3.10 ± 0.52; all values in mas) for which Sahu (1992) derived proper motions and statistical parallaxes. With the exception of HD 68657 (and γ^2 Vel) her values are within 1 σ of the *HIPPARCOS* measurements. The unexpectedly large annual parallax of γ^2 Vel thus lies well within the range covered by other stars that, as shown by Sahu (1992), are likely members of the association Vela OB2. On the basis of our limited data (no new proper motions), there is no evidence against the membership of γ^2 Vel to this group of objects. Given the very small number of objects and the apparently large distance spread determined from the annual parallaxes, this association seems, however, to be quite loosely defined. Despite these uncertainties, an age of about 20 to 30 Myr (Eggen 1980; Sahu 1992) is usually estimated. For the objects mentioned above we obtain individual ages between about 6–30 Myr from Geneva photometry and the *HIPPARCOS* data. For the majority we favor about 10 Myr, which is also supported by recent kinematic observations of the Vela shell (Churchwell et al. 1996).

[6] Adopting our 1 σ error on d of ζ Pup, the distance of Vela R2 must be $\lesssim$580 pc.

Single-star evolution models fail to explain the formation of the γ^2 Vel system for ages $\gtrsim$6 Myr (see Schild & Maeder 1984). A young age is, however, compatible with our estimate for the O star.

An older age of about 10 Myr as typical for other Vela OB2 stars would exclude a large total mass of the system (∼50–60 $M_\odot$). On the other hand, $M_{\rm tot} \sim 30\ M_\odot$ might be compatible with 10 Myr if WR 11 evolved from a intermediate-mass progenitor through mass transfer in the binary system. However, the relatively large eccentricity of γ^2 Vel may speak against such a scenario. Regrettably, the present data do not allow us to draw more definite conclusions about the formation of the γ^2 Vel system.

We thank A. Kaufer, J. Schweickhardt, O. Stahl, and B. Wolf for the spectra of γ^2 Vel obtained with HEROS at the ESO 0.5 m telescope, and V. Niemela for discussions on spectral classification. D. S. wishes to thank Georges Meynet, Jean-Claude Mermilliod, Claus Leitherer, and Jürgen Knödlseder for useful discussions. Travel support from the Geneva Observatory and an invitation from the Université Paul-Sabatier in Toulouse, where part of this work was carried out, are gratefully acknowledged. D. S. receives a fellowship from the Swiss National Foundation of Scientific Research and partial support from the Directors Discretionary Research Fund of the STScI.

REFERENCES

Arenou, F., et al. 1995, A&A, 304, 52
Aschenbach, B., Egger, R., & Trümper, J. 1995, Nature, 373, 587
Baade, D., Schmutz, W., & van Kerkwijk, M. 1990, A&A, 240, 105
Brandt, J. C., Stecher, T. P., Crawford, D. L., & Maran, S. P. 1971, ApJ, 163, L99
Brownsberger, K. R., & Conti, P. S. 1993, in ASP Conf. Proc. 35, Massive Stars: Their Lives in the Interstellar Medium, ed. J. P. Cassinelli & E. B. Churchwell (San Francisco: ASP), 275
Bruhweiler, F. C., Kafatos, M., & Brandt, J. C. 1983, Comments Astrophys., 10, 1
Churchwell, E., Winnberg, A., Cardell, J., Cooper, G., & Suntzeff, N. B. 1996, ApJ, 469, 209
Conti, P., & Smith, L. F. 1972, ApJ, 172, 623
Diehl, R., et al. 1995, A&A, 298, L25
Eenens, P. R. J., & Williams, P. M. 1994, MNRAS, 269, 1082
Eggen, O. J. 1980, ApJ, 238, 627
European Space Agency. 1997, The *HIPPARCOS* Catalogue (ESA SP-1200)
Fitzpatrick, E. L., & Spitzer, L., Jr. 1994, ApJ, 427, 232
Franco, G. A. P. 1990, A&A, 227, 499
Gayley, K. G., Owocki, S. P., & Cranmer, S. R. 1997, ApJ, 475, 786
Hanbury Brown, R., Davis, J., Herbinson-Evans, D., & Allen, L. R. 1970, MNRAS, 148, 103
Howarth, I. D., & Schmutz, W. 1992, A&A, 261, 503
Howarth, I. D., Siebert, K. W., Hussain, G. A. J., & Prinja, R. K. 1997, MNRAS, 284, 265
Kaufer, A., Schweickhardt, J., Stahl, O., & Wolf, B. 1997, private communication
Koesterke, L., & Hamann, W.-R. 1995, A&A, 299, 503
Langer, N. 1989, A&A, 220, 135
Leitherer, C., Chapman, J. M., & Koribalski, B. 1997, ApJ, 481, 898
Lindegren, L. 1995, A&A, 304, 61
Liseau, R., Lorenzetti, D., Nisini, B., Spinoglio, L., & Monetti, A. 1992, A&A, 265, 577
Mathys, G. 1988, A&AS, 76, 427
Meynet, G., Arnould, M., Prantzos, N., & Paulus, G. 1997, A&A, in press
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Moffat, A. F. M., Vogt, N., Paquin, G., Lamontagne, R., & Barrera, L. H. 1986, AJ, 91, 1386
Niemela, V. S., & Sahade, J. 1980, ApJ, 238, 244
Oberlack, U., Diehl, R., Montmerle, T., Prantzos, N., & von Ballmoos, P. 1994, ApJS, 92, 433
Pauldrach, A. W. A., Kudritzki, R. P., Puls, J., Butler, K., & Hunsinger, J. 1994, A&A, 283, 525
Pike, C. D., Stickland, D. J., & Willis, A. 1983, Observatory, 103, 154
Sahu, M. 1992, Ph. D. thesis, Univ. Groningen, Netherlands
Sahu, M., & Blaauw, A. 1993, in ASP Conf. Proc. 35, Massive Stars: Their Lives in the Interstellar Medium, ed. J. P. Cassinelli & E. B. Churchwell (San Francisco: ASP), 278
Schaerer, D., & Maeder, A. 1992, A&A, 263, 129
Schaerer, D., & Schmutz, W. 1994, A&A, 288, 231
Schild, H., & Maeder, A. 1984, A&A, 136, 237
Schmutz, W. 1996, in 33rd Liège International Astrophys. Colloq., Wolf-Rayet Stars in the Framework of Stellar Evolution, ed. J. M. Vreux et al. (Liège: Univ. Liège), 553
———. 1997, A&A, 321, 268
Schmutz, W., Hamann, W.-R., & Wessolowski, U. 1989, A&A, 210, 236
Schmutz, W., & Vacca, W. D. W. 1991, A&AS, 89, 259
Smith, L. F., & Maeder, A. 1989, A&A, 211, 71
Smith, L. F., Meynet, G., & Mermilliod, J.-C. 1994, A&A, 287, 835
Stevens, I. R., Corcoran, M. F., Willis, A. J., Skinner, S. L., Pollock, A. M. T., Nagase, F., & Koyama, K. 1996, MNRAS, 283, 589
St. Louis, N., Drissen, L., Moffat, A. F. J., Bastien, P., & Tapia, S. 1987, ApJ, 322, 870
Vacca, W. D. W., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
van der Hucht, K., Hidayat, B., Admiranto, A. G., Supelli, K. R., & Doom, C. 1988, A&A, 199, 217
van der Hucht, K., et al. 1997, A&A, submitted
van Rensbergen, W., Vanbeveren, D., & de Loore, C. 1996, A&A, 305, 825