RevMexAA (Serie de Conferencias), **5**, 61–67 (1996)

COLLIDING STELLAR WINDS: A NEW METHOD OF DETERMINING MASS-LOSS RATES VIA X-RAY SPECTROSCOPY

Ian R. Stevens
School of Physics and Space Research, Birmingham University,
Birmingham B15 2TT, UK

RESUMEN

La determinación precisa de tasas de pérdida de masa para estrellas Wolf-Rayet (WR) es uno de los objetivos importantes de la investigación en estrellas calientes y un tema en el cual la colisión de vientos en binarias jugará un rol relevante en el futuro. El método más común para determinar tasas de pérdida de masa usa la emisión térmica de radio. Se discuten algunas incertezas presentes en nuestra actual comprensión de este método, así como nuevos resultados de emisión de radio en sistemas con colisión de vientos. Se presentan nuevos espectros *ASCA* de γ Velorum y se describe un nuevo método para la determinación de tasas de pérdida de masa en estrellas WR usando espectroscopía de rayos X en combinación con modelos hidrodinámicos de colisión de vientos. El valor determinado para la componente WR de γ Vel es $\dot{M}_{wr} = 2 - 3 \times 10^{-5}\, M_{\odot}\ \mathrm{yr}^{-1}$.

ABSTRACT

Accurate determinations of Wolf-Rayet (WR) mass-loss rates are an important goal of hot star research, and one in which colliding wind binaries will play an important role in future. The most common current method of determining mass-loss rates uses thermal radio emission, and current uncertainties in our understanding of this method as well as new results on radio emission from colliding wind systems will be discussed. New *ASCA* spectra of γ Velorum will be presented, and a new method of determining WR mass-loss rates using X-ray spectroscopy in conjunction with hydrodynamic models of colliding winds will be described. The determined value for the WR component of γ Vel is $\dot{M}_{WR} = 2-3\times 10^{-5}\, M_{\odot}\ \mathrm{yr}^{-1}$.

Key words: **STARS: INDIVIDUAL (γ VELORUM) — STARS: MASS-LOSS — STARS: WOLF-RAYET — X-RAYS: STARS**

1. INTRODUCTION

Colliding stellar winds in binary systems are now recognised as an integral part of our understanding of hot stars. Signatures of colliding winds have been found at virtually all wavelengths, and in a variety of guises, ranging from X-ray emission directly from the shocked region, to IR emission from dust formation inferred to be a consequence of wind collision. However, in many respects our understanding of colliding winds is rather qualitative, and while the study of WR stars has told us much about colliding winds, our study of colliding winds has yet to tell us much about WR stars and their winds. However, this situation is beginning to change on a number of fronts, and it is now becoming possible to determine fundamental wind parameters of WR stars through their colliding wind emission.

Accurate determinations of mass-loss rates remains an important goal of hot star research. In § 2 I highlight the major discrepancies that exist between current methods of determining mass-loss rates. Radio emission remains probably the most used method, though there are some important uncertainties in the values of $\dot{M}$ derived (see § 3). For instance, the effect of binarity on thermal radio emission has received scant attention, and this is discussed in § 3.4. In § 4 I will describe new X-ray results from *ASCA* observations of one important colliding wind system (γ Vel). By modelling these spectra using synthetic spectra calculated from hydrodynamic models of colliding winds it is possible to determine a new and independent value of the WR star mass-loss rate. This method, discussed in § 5, represents the first time that WR mass-loss rates have been determined by X-ray spectroscopy.

TABLE 1

MASS-LOSS RATES FOR V444 CYG

Method	$\dot{M}(M_\odot\ \mathrm{yr}^{-1})$	Authors
Dynamical	1.0×10^{-5}	Khaliullin et al.1984
	0.4×10^{-5}	Underhill et al.1990
Polarization	0.8×10^{-5}	St-Louis et al.1993
IR Spectroscopy	$2 - 5 \times 10^{-5}$	Howarth & Schmutz 1992
Thermal Radio	2.4×10^{-5}	Prinja et al.1990

2. WOLF-RAYET MASS-LOSS RATES

There is no doubt that the mass-loss rate for WR stars is large, but how large? A literature survey reveals that several different methods of determining $\dot{M}$ for WR stars are in use and, that there are *major* discrepancies between the methods. This is important because errors in $\dot{M}$ determinations can have, for example, a potentially large impact on stellar evolution calculations. To illustrate this, in Table 1 are values of $\dot{M}$ taken from the literature for V444 Cyg (perhaps the best studied binary WR star). Some of the methods in Table 1 are applicable to single WR stars (thermal radio/IR spectroscopy), while some are applicable only to binaries (dynamical/polarization). However, all of the methods in Table 1 have some potential drawbacks that could lead to inaccuracies. In § 3 some of the problems associated with determinations using thermal radio emission will be discussed. However, the discrepancies shown in Table 1 make it clear that there are still considerable uncertainty in WR mass-loss rates, and that there is room for additional independent methods to determine WR mass-loss rates, and one of the goals of this paper is to present a new method involving modelling of X-ray spectra.

3. THERMAL RADIO EMISSION

Thermal radio emission is perhaps the most common method used to determine WR mass-loss rates, and this is in part a consequence of the simple relationship between flux (S_ν) and mass-loss rate ($\dot{M}$) found by Wright & Barlow (1975):

$$S_\nu(\mathrm{Jy}) = 23.2 \left(\frac{\dot{M}}{\mu_i v_\infty}\right)^{4/3} \frac{\nu^{2/3}}{D^2} \gamma^{2/3} g_{ff}^{2/3} Z^{4/3} , \tag{1}$$

where $\dot{M}$ is in units of $M_\odot\ \mathrm{yr}^{-1}$, v_∞ in km s^{-1}, D in kpc, ν in Hz, γ is ratio of electron to ion number density, g_{ff} is Gaunt factor, μ_i the mean mass per ion, and Z the mean charge per particle. This expression was derived for single WR stars with a spherically symmetric wind, but has been used in a rather blanket fashion for both single and binary WR stars. Some of the sources of uncertainty in thermal radio emission determinations of $\dot{M}$ will be discussed below, as well as new results of the theoretically expected thermal radio emission from colliding wind binaries.

3.1. Clumping/Wind Inhomogeneities

Consider a clumpy wind, consisting of two phases: high density regions with a density n_H and filling factor f, and low density regions with a density n_L. If $x = n_L/n_H$ then

$$S_\nu(\mathrm{clumpy}) = S_\nu(\mathrm{smooth}) \left[\frac{f + (1-f)\,x^2}{(f + x\,(1-f))^2}\right]^{2/3} \tag{2}$$

For example, for $f = 0.5$, $x = 0.1$, radio emission is increased by 40%. This will lead to a 30% error in $\dot{M}$ (if the wind is assumed to be smooth). In a wind with very diffuse interclump media ($x \to 0$) then $S_\nu \propto f^{-2/3}$. The major difficulty is that there is no method of estimating the degree of clumping in the radio region. There is clear evidence of clumping closer into the star (such as Discrete Absorption Components), but whether these

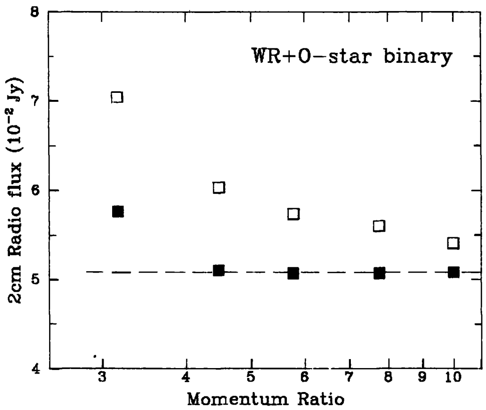

Fig. 1. The theoretical 2 cm thermal radio flux for colliding wind binary systems for a Wolf-Rayet + O-star binary system, as a function of the wind momentum ratio $\mathcal{R}$. The open squares represent the flux at phases when the WR star is behind the O-star ($\phi = 0.5$), and the filled squares when the WR is in front ($\phi = 0.0$). The dashed line represents the expected radio flux from a single WR-star with the same wind parameters as the primary ($S_\nu = 5.09 \times 10^{-3}$Jy).

clumps smooth out or amplify with distance is unclear. Consequently, the degree to which clumping will affect the determined mass-loss rates is uncertain, except that the assumption of a smooth wind will lead to an overestimate of $\dot{M}$ if there is any degree of clumping in the wind.

3.2. Ionization Balance in the Radio Region

The ionization state of the wind material, particularly whether the dominant ion in the radio emitting region is He^+ or He^{2+}. However, work by Schmutz et al. (1989) has found that He^+ is the dominant ion in the radio forming region of most WR stars (with the exception of the hottest WR stars). This issue is probably not now a major source of uncertainty.

3.3. Contamination with Non-Thermal Emission

A number of WR+O-star binaries exhibit both thermal and non-thermal radio emission (WR140, Williams et al. 1990: WR147, Churchwell et al. 1992). For single frequency observations there is the potential for confusion. However, multiwavelength observations should be able to disentangle the thermal component (i.e., Churchwell et al. 1992), and again this should not be a major source of uncertainty.

3.4. Thermal Radio Emission from Colliding Wind Binaries

Stevens (1995) has discussed results of calculations of the expected thermal emission from colliding wind binary systems. The basic method was an extension of the original Wright & Barlow (1975) formalism. Details of the method will not be given here and readers are referred to Stevens (1995). These calculations include the effect of two distinct winds, each with a different velocity/density structure and different abundances, Also included is the emission from the hot intershock region. This region although being hot, and hence having a lower free-free opacity at radio frequencies ($\kappa_{ff} \propto T^{-3/2}$) is also substantially denser than the adjacent wind regions ($\kappa_{ff} \propto n^2$). These two effects tend to cancel each other out and the hot intershock region makes an important contribution to the thermal radio emission and cannot be ignored).

The calculations presented in Stevens (1995) are only directly applicable for two binary phases ($\phi = 0$ and $\phi = 0.5$), for circular orbits and for wide binary systems (where the intershock region is adiabatic). However, in spite of the limitations they can be indicative of expected behaviour in a wide range of systems. In Fig. 1, results are shown for WR+O-star binaries for a range of wind momentum ratio $\mathcal{R}$. The main result are as follows:

1. Binarity tends to increase the radio flux compared to that for a single star with the same parameters as the primary. In addition to there simply being more material in the system, the hot gas from the wind collision also contributes.

2. In binary systems where one star has a dominant wind, the effect on S_ν is not great (typically less than 20 percent), though in systems with comparable mass-loss rates it can be as much as much as 50 percent.

3. Some orbital variability in thermal radio emission is to be expected in WR+O-star binaries, at the level of $10 - 20\%$, with the system being more luminous when the O-star is in front.

In summary, binarity will affect thermal radio emission from colliding wind binaries, though not by a huge factor, and in WR+O-star binaries emission from the WR star will dominate. In many systems it will be possible to apply a correction for binarity, although uncertainties associated with clumping will likely be larger. In the next sections I will describe X-ray observations of γ Vel and show how such observations can be used to determine WR mass-loss rates and other wind parameters.

TABLE 2

SPECTRAL FITS TO THE ASCA OBSERVATIONS OF γ VELORUM

Parameter	Date of Observation May 17 1994	May 25 1994
kT_1 (keV)	1.36 ± 0.21	1.20 ± 0.03
$N(H)_1$ (10^{22} cm^{-2})	6.91 ± 1.03	2.92 ± 0.17
kT_2 (keV)	0.28 ± 0.04	0.27 ± 0.04
$N(H)_2$ (10^{22} cm^{-2})	0.98 ± 0.08	1.58 ± 0.10
χ^2_ν (d.o.f)	1.37 (235)	1.11 (440)
L_x [0.5 – 10 keV] (erg s^{-1})	8.70×10^{31}	3.61×10^{32}

4. X-RAY OBSERVATIONS OF γ VELORUM

γ Vel is a binary system (WC8+O9I) in an eccentric ($e = 0.4$) 78.5 day orbit. The system is the closest and brightest WR star, is an important colliding wind system, and has been the subject of an intensive X-ray campaign with both the *ROSAT* and *ASCA* satellites.

4.1. ROSAT Observations

γ Vel has been observed a total of 13 times with *ROSAT*. Results from this campaign have been presented in Willis et al. (1995), and can be summarised as follows:

1. For most of the orbit γ Vel was seen as a weak, soft ($kT \sim 0.2$ keV) source. This emission is probably the same as that seen from all early-type stars (shocks due to radiative driving instabilities).

2. Near $\phi = 0.4 - 0.6$ (O-star in front of WR star) the source shows a sharp flux increase (factor $\times 4$), with the additional flux comes from a harder, absorbed component, interpreted as being from colliding winds.

3. We only see this harder component at phases when we are looking through the O-star wind (around $\phi = 0.4 - 0.6$). At other phases the dense WR wind effectively absorbs it.

4. The hard component has a temperature > 1 keV, but its precise temperature is not well constrained by *ROSAT*.

5. The most likely explanation is that we are seeing X-ray emission from the wind collision, which can only be seen with *ROSAT* at phases when we are observing through the O-star wind.

4.2. ASCA Observations

The Japanese *ASCA* satellite has somewhat different capabilities than the *ROSAT* satellite. Its spatial resolution is somewhat poorer (~ 3 arc minutes), but its spectral resolution is much better, and it has a wider

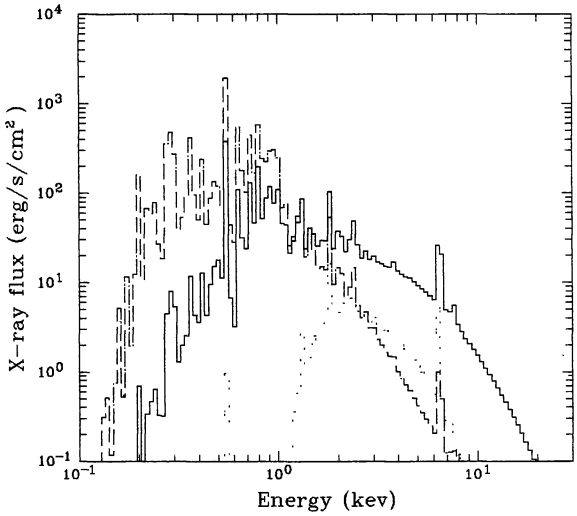

Fig. 2. Sample synthetic spectra calculated for γ Vel using the hydrodynamic simulations of colliding winds. The synthetic spectra are shown for phase $\phi = 0.5$ and for models with the following parameters. a) $\dot{M}_{WR} = 9 \times 10^{-5}\, M_\odot\ \mathrm{yr}^{-1}$, $\dot{M}_O = 5 \times 10^{-6}\, M_\odot\ \mathrm{yr}^{-1}$, $v_\infty(WR) = 1500\,\mathrm{km\ s^{-1}}$, and $v_\infty(O) = 2400\,\mathrm{km\ s^{-1}}$ (full line) b) $\dot{M}_{WR} = 9 \times 10^{-5}\, M_\odot\ \mathrm{yr}^{-1}$, $\dot{M}_O = 5 \times 10^{-6}\, M_\odot\ \mathrm{yr}^{-1}$, $v_\infty(WR) = 1500\,\mathrm{km\ s^{-1}}$, and $v_\infty(O) = 1000\,\mathrm{km\ s^{-1}}$ (dotted line) c) $\dot{M}_{WR} = 9 \times 10^{-5}\, M_\odot\ \mathrm{yr}^{-1}$, $\dot{M}_O = 5 \times 10^{-7}\, M_\odot\ \mathrm{yr}^{-1}$, $v_\infty(WR) = 1500\,\mathrm{km\ s^{-1}}$, and $v_\infty(O) = 2400\,\mathrm{km\ s^{-1}}$ (dot-dashed line).

bandwidth ($0.5 - 10$ keV). The hard emission observed with *ROSAT* at $\phi = 0.5$ made γ Vel a prime target for *ASCA* observations. Two 20 ksec observations have been made, at phases $\phi = 0.4$ and 0.5 (when the O-star was generally in front of the WR star), on May 17 and May 25 1994. The data have been reduced and analysed, and a paper (Stevens et al. 1996) is in preparation describing these results.

In line with previous analyses of X-ray observations of colliding wind systems we initially fit these spectra with Raymond-Smith type spectral models. We were able to fit these spectra using two temperature Raymond-Smith models, each with a separate column, and the results are given in Table 2. These results are in line with the *ROSAT* observations, with a factor 4 increase in flux between $\phi = 0.4$ and 0.5. What is interesting is that there are two spectral components, one soft $kT \sim 0.3$ keV, which has a column of around 10^{22} cm^{-2}, and a harder component $kT \sim 1.2$ keV, which has a much higher column at $\phi = 0.4$ than at $\phi = 0.5$. These results are again consistent with a colliding wind model where we primarily observed the emission from the shock only at phases around $\phi = 0.5$. The harder response of *ASCA* means that we see some additional, highly absorbed X-ray emission at $\phi = 0.4$ which we could not see with *ROSAT*.

5. A NEW METHOD OF DETERMINING WOLF-RAYET MASS-LOSS RATES

Rather than just stopping at these simple two temperature fits, we can analyse the data in a far more sophisticated manner using hydrodynamical models of colliding winds. As will become apparent this approach, in addition to being more physically realistic, has the potential for yielding physical insight into colliding winds, and determining stellar wind parameters of the component stars.

The basic approach is to use hydrodynamic models of colliding winds to calculate synthetic spectra and then fit the *ASCA* spectra. The procedure we have adopted is as follows:

1. Define a grid of stellar wind parameters —the mass-loss rates and terminal velocities of the winds of the two stars— making a total of 4 free parameters.

2. Calculate hydrodynamic models for γ Vel for each set of wind parameters in the same way as was done in Stevens et al. (1992).

3. Using these hydrodynamic models we calculate synthetic spectra for each set of grid parameters at both orbital phases of the observations (see Fig. 2).

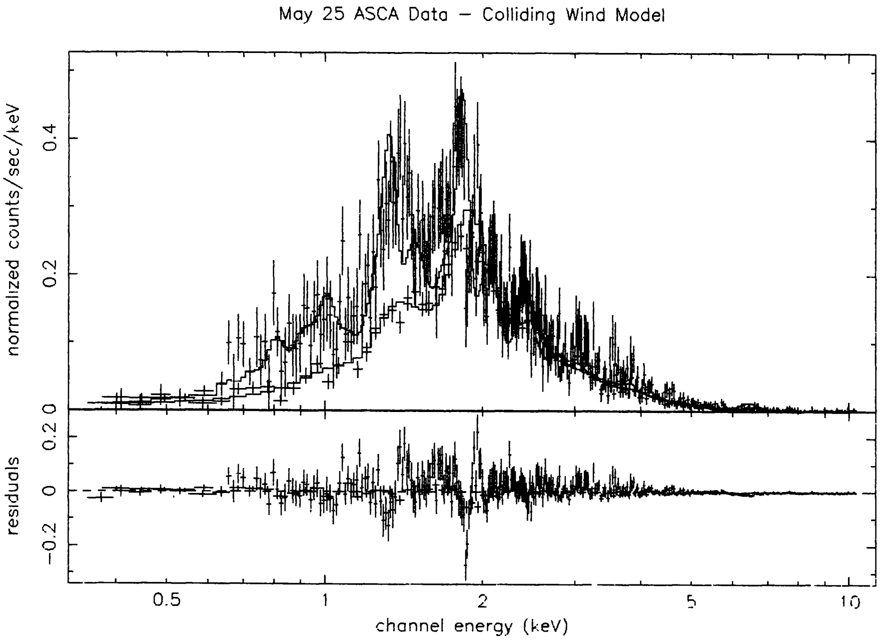

Fig. 3. Spectral fit to the May 25 *ASCA* observations (both SIS and GIS instruments) of γ Vel using the synthetic spectra. The results are those in Table 3, and are for the colliding wind synthetic spectral model plus an additional Raymond-Smith spectral component.

4. We independently fit the *ASCA* spectra at both $\phi = 0.4$ and 0.5 with the synthetic spectra to obtain the best parameters (see Fig. 3).

5. To account for the soft emission (which is probably not generated by colliding winds), we add an additional soft component ($kT \sim 0.2 - 0.3$ keV) with a separate absorbing column. This component is likely the emission from the stochastic shocks that are present in all radiatively driven winds.

6. We also include interstellar absorption with a column of 8×10^{19} cm^{-2} for both spectral components.

In Fig. 2 some examples of the synthetic spectra calculated from the hydrodynamic models are shown for three different sets of parameters. The luminosity and spectra are complex functions of the winds parameters, but in general higher wind velocities lead to a harder spectrum, and higher mass-loss rates lead to more low energy absorption. We have performed the procedure outlined above independently for both the *ASCA* spectra and the results from this fitting are shown in Table 3, and the best fit to the $\phi = 0.5$ data are shown in Fig. 3.

There are several points to note from Table 3. Some of the wind parameters are not very well determined by the fitting procedure, and some of the parameter values had to be fixed to obtain a fit. However, the most important parameter, the WR mass-loss rate, does seem to be well constrained to have a value of around $2 - 3 \times 10^{-5} M_{\odot}$ yr^{-1} with a fair measure of consistency between the independent fits at $\phi = 0.4$ and 0.5. This is an important result and represents the first determination of WR mass-loss rates by means of X-ray spectroscopy. This value of $\dot{M}_{WR}$ will be discussed more in the next section. This technique is still in its infancy and considerable refinements to the synthetic spectra can be made, which will make the technique more reliable.

6. DISCUSSION AND SUMMARY

In the previous section a new method of determining WR mass-loss rates was introduced and the first results presented. This is a new technique and the results should be treated with caution. For example, several major improvements should be made to the hydrodynamic models used to generate the synthetic spectra; 1) including accelerating winds (including the effects of both radiation fields on the winds) rather than the terminal

TABLE 3

COLLIDING WIND MODEL FITS TO THE *ASCA* OBSERVATIONS OF γ VEL

Parameter	Date of Observation May 17 1994	May 25 1994
$\dot{M}_{WR}$ ($10^{-5}\,M_{\odot}$ yr^{-1})	2.06 ± 0.35	2.91 ± 0.74
$\dot{M}_{O}$ ($10^{-6}\,M_{\odot}$ yr^{-1})	5.0	3.55 ± 0.40
$v_{\infty}(WR)$ (km s^{-1})	1000	1500
$v_{\infty}(O)$ (km s^{-1})	2184 ± 3550	1498 ± 116
kT (keV)	0.07 ± 0.05	0.28 ± 0.09
N_H (10^{22} cm^{-2})	1.23 ± 0.46	0.05 ± 0.33
χ^2_{ν} (d.o.f)	1.48 (234)	1.37 (439)
L_x [0.5 - 10 keV] (erg s^{-1})	1.25×10^{32}	3.76×10^{32}

velocity winds that are currently in the model, and 2) including binary rotation in a self consistent manner rather than the current *ad hoc* manner. It is also planned to apply this technique to other systems such as WR140 where there is also *ASCA* data available. In this case, because the binary system is wider, we may expect more accurate results from such modelling.

In spite of these limitations the determined value of the WR mass-loss rate is very interesting. It is a factor ~ 3 lower than the thermal radio value of $8.8 \times 10^{-5}\,M_{\odot}$ yr^{-1} (Barlow et al. 1988). It is worth noting that the values determined by polarization studies are also typically a factor few lower than radio values in the limited number of cases where a comparison is possible. Both this X-ray spectroscopic technique and polarization measurements are likely to be less susceptible to the effects of clumping than radio techniques, and this may be indicative that radio observations are substantially overestimating mass-loss rates (though this assertion is of course very tentative and much more work is needed on this technique before it can be considered reliable).

In summary, in this paper I have discussed some of the potential problems with radio determinations of WR mass-loss rates, with an emphasis on clumping, and the effect of binarity has on colliding wind thermal radio emission. The main thrust of this paper has been to present recent X-ray observations of an important colliding wind system (γ Vel) and a new modelling techniques (using complex hydrodynamic models) which has enabled, for the first time, the determination of the mass-loss rate of the WR star via X-ray spectroscopy. The determined value is $\dot{M}_{WR} = 2 - 3 \times 10^{-5}\,M_{\odot}$ yr^{-1}, and it is substantially lower than previous radio determinations.

REFERENCES

Barlow, M. J., Roche, P. F., & Aitken, D. K. 1988, MNRAS, 232, 821
Churchwell, E., Bieging, J. H., Van der Hucht, K. A., Williams, P. M., Spoelstra, T. A. Th., & Abbot, D. C. 1992, ApJ, 393, 329
Howarth, I. D., & Schmutz, W. 1992, A&A, 261, 503
Khaliullin, Kh. F., Khaliullina, A. I., & Cherepashchuk, A. M. 1984, Sov. Astr. Lett., 10, 250
Prinja, R. K., Barlow, M. J., & Howarth, I. D. 1990, ApJ, 361, 607
St-Louis, N., Moffat, A. F. J., Lapointe, L., Efimov, Yu. S., Shakhovskoj, N. M., Fox, G. K., & Piirola, V. 1993, ApJ, 410, 342
Schmutz, W., Hamann, W.-R., & Wessolowski, U. 1989, A&A, 210, 236
Stevens, I. R. 1995, MNRAS, 277, 163
Stevens, I. R., Blondin, J. M., & Pollock, A. M. T. 1992, ApJ, 386, 265
Stevens, I. R., Corcoran, M. F., Willis, A. J., Skinner, S., Pollock, A. M., Nagase, F., & Koyama, K 1996, MNRAS, in press
Underhill, A., Grieve, G. R., & Louth, H. 1990, PASP, 102, 749
Williams, P. M., van der Hucht, K. A., Pollock, A. M., Florkowski, D. R., van der Woerd, H., & Wamstecker, W. M. 1990, MNRAS, 243, 662
Willis, A. J., Schild, H., & Stevens, I. R. 1995, A&A, 298, 549
Wright, A. E., & Barlow, M. J. 1975, MNRAS, 170, 41