Clumping in Hot Star Winds
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Do clumping corrections increase with decreasing mass-loss rates?

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We report on new mass-loss rate estimates for O stars in six massive binaries using the amplitude of orbital-phase dependent, linear-polarimetric variability caused by electron scattering off free electrons in the winds. Our estimated mass-loss rates for luminous O stars are independent of clumping. They suggest similar clumping corrections as for WR stars and do not support the recently proposed reduction in mass-loss rates of O stars by one or two orders of magnitude.

1 Introduction

There are many ways to estimates mass-loss rates of massive stars. For some time, it was thought that rates obtained from fitting recombination lines such as H_α (e.g. Markova et al. 2004) or based on radio/IR free-free emission fluxes (Wright & Barlow 1975) were the most accurate. However, when winds were discovered to be clumpy, it was realised that these two methods actually overestimate mass-loss rates, as they depend on the square of the wind density.

Therefore, other methods were sought to alleviate this problem. Fullerton et al. (2006) fitted line profiles to the Pv resonance doublet of 40 Galactic O stars. The advantage of using these lines is that P^{+4} is a trace ion in the wind of massive O stars, which insures that the line is not saturated. However, the estimated values of the mass-loss rates were found to be surprisingly low; reduction factors have a median value of ~20 for O4 to O7 stars and ~130 for O7 to O9.7 stars. To check if mass-loss rates of O stars need to be so drastically reduced, other methods need to be used.

Alternative methods to get reliable clumping-independent mass-loss rates involve binary systems. Of course, the method that is the most direct is the orbital period lengthening due to symmetric mass-loss as used, for example, by Khaliullin (1974). However, this requires extremely long timescales as the period changes are very small. Another method, suggested by Lamontagne et al. (1996), is the modelling of atmospheric eclipses. The companion star's light shines through the wind and the depth of the light-curve variation depends on the density in the wind and therefore on the mass-loss rate.

Finally, St-Louis et al. (1988) devised a method based on linear polarisation variability as a function of orbital phase for massive WR+O binaries. This method has the advantage that the detailed fit of the polarisation modulation provides an estimate of the orbital inclination (Brown et al. 1978) while the amplitude of the change gives the mass-loss rates. The basic principle is that in a WR+O binary, the light from the O star acts as a probe of the WR wind via electron scattering. O-star photons scatter off the abundant free electrons in the WR wind, which polarises the light received by the observer. The level of polarisation of the observed light depends on the angle between the O-star light source and the scatterers in the WR wind (i.e. the orbital phase for circular orbits) and the total number of scatterings and therefore on the number of free electrons. This latter value is in turn related to the mass-loss rate of the WR star via some simple assumptions. St-Louis et al. (1988) have shown that:

$$\dot{M} = \frac{2.33 \times 10^{-7} A_p \; a(R_\odot) v_\infty (\mathrm{km\ s^{-1}})}{(1+\cos^2 i) f_c I} M_\odot/yr,$$

where A_p is the semi-amplitude of the polarisation ellipse in the Q-U plane, a is the semi-major axis of the orbit, v_∞ is the terminal velocity of the WR wind, i is the orbital inclination, f_c is the fraction of the total flux coming from the companion and I is the numerical value of an integral over solid angles and depends on the β value of the velocity law and the radius beyond which single electron scattering dominates.

Here we have adapted this formalism to O+O binaries. We have searched for published linear polarisation curves in the literature and came up with a sample of 6 massive O binaries, whose names are listed in Table 1. Also given are their orbital period, spectral type, flux fraction for the less luminous of the two stars, the orbital inclination, the semi-major axis of the orbit and the terminal velocity of the dominant wind. All references are given as footnotes. The last parameter that must be specified is the number of free electron per nucleon, α. Here we have assumed in all cases that hydrogen is

Table 1: Data and mass-loss rate estimates for our sample of massive O stars

Star	HD 149404	HD 152248	HD 47129 Plasket's Star	HD 57060 29 CMa	Sk-67^{o}105 (LMC)	LSS 3074
Orbital Period (d)	9.81	5.81	14.40	4.39	3.30	2.185
Spectral Type	O8.5I +O6.5III	O7.5III(f) +O7III(f)	O7.5I +O6I	O7.5Iab +O9.7Ib	O4f +O6V	O4f +O6-7
f$_c$	0.5^2	0.5^4	0.5^6	0.24^{10}	0.31	0.4
i(^{o})	30^2	72^4	71^7	74^{10}	71.5	50
a(R$_\odot$)	62^2	54^4	119^8	37^{11}	42	20.6
v$_\infty$$(km/s)$	2300^1	2200^5	2400^9	1425^5	2500	2500
A$_p$	0.002^3	0.0006^3	0.0002^7	0.0015^{12}	0.0145	0.0125
I	12	12	12	12	12	12
α	1	1	1	1	1	1
$\dot{\rm M}$(M$_\odot$)	**3.1×10^{-6}**	**2.3×10^{-6}**	**1.8×10^{-6}**	**11×10^{-6}**	**21×10^{-6}**	**3.1×10^{-6}**

[1] Penny (1996) [2] Penny et al. (1999a) [3] Luna (1988) [4] Penny et al. (1999b) [5] Howarth et al. (1997) [6] Bagnuolo et al. (1992) [7] Rudy & Herman (1978) [8] Stickland (1987) [9] Prinja et al. (1990) [10] Bagnuolo et al. (1994) [11] Based on the masses of Bagnuolo et al. (1994) [12] Lupie & Nordsieck (1987)

the dominant ion and that it is fully ionised, leading to a value of $\alpha = 1$. The value of the integral I is taken from St-Louis et al. (1988). We have adoted a value of $\beta = 0.8$. In all cases, the value of a/R_* was found to be around 2, leading to a value of $I = 12$.

In the case of WR+O binaries, the wind of the O star is assumed to be negligible with respect to that of the WR star and therefore only the electron scattering of O star photons by WR-wind free electrons is taken into account. In the case of O+O binaries, the two winds can have comparable strengths and therefore both must be taken into account. Most of the binary sytems in our sample are very well studied, which gave us a good idea of the relative strengths of the two winds. In several cases, we have assumed equal-strength winds. In such a situation, the polarisation variability is the result of scattering off photons in the two winds and consequently, the published polarisation amplitude must be divided by two. For a given mass-loss rate of one of the O stars, the polarisation amplitude is therefore doubled (in relative terms) compared to the case of a WR+O binary. This partly compensates for the fact that the mass-loss rates of O stars are generally much smaller than those of WR stars and therefore the absolute values of the linear-polarisation amplitudes are smaller. In Figure 1 we show an example of Q and U curves. The data are for the O8.5I+O6.5III binary HD 149404 and are reproduced from Luna (1988). The characteristic double-wave curve is clearly seen. The literature values of the polarisation amplitudes, A_p, for the 6 binaries in our sample are given in Table 1.

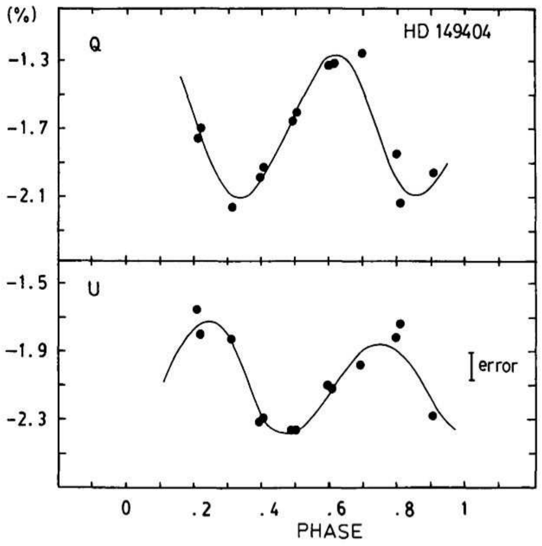

Figure 1: Q and U as a function of orbital phase for the O8.5I+O6.5III binary HD 149404. Reproduced from Luna (1988).

The values of the mass-loss rates that we obtain from the equation of St-Louis et al. (1988) given above are listed in the last line of Table 1. For the first three stars, we have assumed equal winds and therefore the value given is for each component. For the last three stars, the value of the mass-loss rate is for the primary, as the secondary is assumed to have a negligible wind in comparison to that of the primary. The mass-loss rate values are certainly not two orders of magnitude smaller than average values from free-free emission fluxes or recombination-line fits. Unfortunately, in most cases it is impossible to obtain mass-loss rate estimates by fitting H_α line profiles since, although observed extensively, they are greatly affected by wind-wind collision effects.

Only one of the stars in our sample, HD 149404, has a measured radio thermal flux. The initial mass-loss estimate from Lamers & Leitherer (1993) has been corrected for the revised temperature scale for O dwarfs (Martins et al. 2005) by Fullerton et al. (2006). The resulting value of the mass-loss rate is $\dot{\rm M}$=6.17 $\times 10^{-6}$ $M_\odot$/yr. However, to our knowledge, this estimate does not take into account that the radio flux actually comes from both O stars taken together; therefore it should be divided by two. Our estimated mass-loss rate for each star in this binary is 3.1 $\times 10^{-6}$ $M_\odot$/yr, which is amazingly similar to the radio value (after dividing by two).

We can also compare our estimated mass-loss rate for HD 149404 with the predictions of Vink et al. (2000). Using their theoretical mass-loss recipe for O-type stars in the temperature range 30000–50000 K and stellar parameters for HD 149404 from Penny et al. (1999a) ($T = 36000\ K, log(L_*) = 5.74, M_* = 17\ M_\odot, R_* = 20\ R_\odot$ and $v_\infty = 2300\ km\ s^{-1}$), we calculate $\dot{M} = 6.5 \times 10^{-6} M_\odot/yr$. The temperature used here is appropriate for an O6.5III star, according to the temperature scale of Martins et al. (2005). If instead we adopt $T = 31000\ K$, which is the value given by Martins et al. (2005) for an O8.5I star, we obtain a slightly lower value for the mass-loss rate, $\dot{M} = 4.4 \times 10^{-6} M_\odot/yr$. These value are quite similar to the polarisation and radio values (3.1 $\times 10^{-6}$ $M_\odot$/yr) considering the number of stellar parameters, each with their own error, that enter into these estimates. Furthermore, these theoretical predictions do not include the effects of clumping and therefore are most likely too high.

On the other hand, from fits to the FUSE-band PV resonance doublet, Fullerton et al. (2006) obtain a value of 5.37 $\times 10^{-8}$ $M_\odot$/yr for this star, when they assume that P^{+4} is the dominant P ion in the wind, a value two orders of magnitude below the two above-mentioned estimates. No other star in our sample is also part of the sample of Fullerton et al. (2006).

Therefore the polarisation mass-loss rate estimates do not support a reduction in the mass-loss rates of O stars by two orders of magnitude, at least for the most luminous O stars such as those we have in our sample.

References

Bagnuolo, W. G. Jr.,Gies, D.R., & Wiggs, M.S. 1992, ApJ, 385, 708

Bagnuolo, W.G., Gies, D.R., Hahula, M.E., Wiemker, R., & Wiggs, M.S. 1994, ApJ, 423, 446

Brown, J.C., McLean, I.S., & Emslie, A.G. 1978, A&A, 68, 415

Fullerton, A.W., Massa, D.L., & Prinja, R.K. 2006, ApJ, 637, 1025

Howarth, I.D., Siebert, K.W., Husain, A.J., & Prinja, R.K. 1997, MNRAS, 284, 265

Khaliullin, K. F. 1974, Astronomicheskii Zhurnal, 51, 395

Lamers, H.J.G.L.M., & Leitherer, C. 1993, ApJ, 412, 771

Lamontagne, R., Moffat, A.F.J., Drissen, L., Robert, C., & Matthews, J.M. 1996, AJ, 112, 2227

Luna, H.G. 1988, A&A Sup. Series, 74, 427

Lupie, O. L., & Nordsieck, K. H. 1987, AJ, 93, 214

Markova, N., Puls, J., Repolust, T., & Markov, H. 2004, A&A, 413, 693

Martins, F., Schaerer, D., & Hillier, D.J. 2005, A&A, 436, 1049

Martins, F., Schaerer, D., & Hillier, D.J. 2005, A&A, 436, 1049

Penny, L.R. 1996, ApJ, 463, 737

Penny, L.R., Gies, D.G., & Bagnuolo Jr, W. G. 1999a, In *Proc. IAU Symp. 193*, 86

Penny, L.R., Gies, D.R., & Baguolo, W.G. Jr. 1999b, ApJ, 518, 450

Prinja, R. K., Barlow, M. J., & Howarth, I. D. 1990, ApJ, 361, 607

Rudy, R.J., & Herman, L.C. 1978, PASP, 90 163

St-Louis, N., Moffat, A.F.J., Drissen, L., Bastien, P., & Bastien, P. 1988, ApJ, 330, 286

Stickland, D. J. 1987, The Observatory, 107, 68

Vink, J.S., de Koter, A., & Lamers, H.J.G.L.M. 2000, A&A, 362, 295

Wright, A. E., & Barlow, M. J. 1975, MNRAS, 170, 41

Hillier: These O stars have significantly weaker winds than other O stars. As a consequence, the optical depth of the wind to electron scattering is low. I was therefore wondering what fraction of the polarization signal comes from scattering off the photosphere.

St-Louis: I have not taken that into account in these estimates. Certainly the mass loss rates will have to be reduced because of this effect, but I do not know what the level of the corrections will be; I would have to work them out.

Cassinelli: The photospheres are optically thick. Therefore, radiation that enters is multiply scattered and so scattering from the photosphere will probably be very small.

Moffat: If clumps are optically thick, then this could also hide electrons. So, does the fact that you observe such relatively large mass loss rates from polarization imply that clumps are not optically thick?

Hillier: The clumps are optically thick to lines but not to electron scattering.