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Rotation and mass loss in early type stars

M. S. Vardya
Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005

Abstract. The effect of rotation on the rate of mass loss for O and B stars has been reviewed, and the causes of conflicting results discussed.

Key words . rotation—mass loss—early type stars

Rotation decreases the effective surface gravity of a star, thereby decreasing the escape velocity. Thus one expects that rotation should enhance the rate of stellar mass loss $\dot{M}$.

Theoretically, de Greve, de Loore & de Jager (1972) showed that the rate of mass loss increases by 26 to 40% for linear rotation velocity v up to 200 km s^{-1} in a F2 V type star. Marlborough & Zamir (1984) modified the CAK theory (Castor, Abbott & Klein 1975) and showed that rotation increases the rate of mass loss over no-rotation value, ugh they did not give any numerical value.

What about the observational evidence? Furenlid & Young (1980) considering 60 rmal main sequence B0-B3 stars (excluding Be and peculiar stars) found that H_α line mmetry, which gives a measure of mass loss, is always large when projected linear ational velocity $v \sin i \geqslant 200$ km s^{-1}, however, they did not consider $\dot{M}$ itself and no inite trend between asymmetry and $v \sin i$ is visible. Snow (1981) analysed 22 B stars om B0.5 to B6) including 19 Be-like stars, Doazan *et al.* (1982) 21 Be, B shell and rmal stars, and Slettebak & Carpenter (1983) 12 Be and standard stars but found no nclusive evidence for rotation enhancing rate of mass loss. Gathier, Lamers & Snow 981) did note a qualitative dependence of $\dot{M}$ on $v \sin i$ in 25 high luminosity O and B rs, but found null result for early B supergiants.

The question naturally arises: Why this lack of definitiveness? Does the answer lie in fact that observations provide projected rotational velocity $v \sin i$ when the theory mands v itself, without the aspect angle effect? And if it is so, how we can circumvent

A large mixed sample of stars should randomize the effect of sin i, making it possible discern the effect of rotation in spite of large individual deviations from the mean due the geometrical effect. All the above mentioned studies had considered not only a very nited number of stars, but in a rather small range of spectral class. Therefore I (Vardya 85) decided to consider a large sample of stars covering a large range in projected tational velocity, luminosity, temperature and rate of mass loss with the hope that sin i ll be randomized as well as possible. A total of 81 stars—49 from Lamers (1981), 14 m Garmany *et al.* (1981) and 18 from Snow (1982)—were considered covering a range temperature spectral class from O3 to B9, luminosity class Ia^+ to V, $v \sin i$ from, 15 to

505 km s^{-1} and $\dot{M}$ from 3×10^{-11} to 2×10^{-5} $M_\odot y^{-1}$. This sample has 21 O stars with f, (f) and ((f)) spectral characteristics, 10 Be stars or 18 Be like stars, and six peculiar stars, with a range of log $L/L_\odot$ from 2.53 to 6.38, $M/M_\odot$ from 7 to 136, and $R/R_\odot$ from 5 to 86. This is a fairly mixed sample, though not a completely unbiased one. Note that all the 18 stars from Snow (1982) appear to have Be-like propeities from the point of view of rate of mass loss In fact, the mean value of $\dot{M}$ for these Be-like stars is about four orders of magnitude less than the rest of the 63 O and B stars, which hereafter we will call normal OB stars

No relation was found between the rate of mass loss and $v \sin i$ but the rate of mass loss per unit area, *i.e*, mass flux was found to correlate with $v \sin i$ There were two separate relations -- one for the 63 normal OB stars and another one for the 18 Be-like stars. Note that the mean value of mass flux for OB stars differ from that of Be-like stars by three orders of magnitude.

Though this was encouraging, it was not satisfactory. Rotation, in a way, is an extrinsic property Therefore, getting two separate relations rather than one was somewhat puzzling. Furthermore, rate of mass loss is four orders of magnitude less or mass flux three orders of magnitude less for Be-like stars relative to normal OB stars, when the mean $v \sin i$ is three times larger for Be-like stars relative to normal OB stars; this implies that other causes of mass loss dominate over rotation. With a hope of achieving one single relation for both groups of stars, it was decided to subtract the dominant cause of mass loss *i e* radiation pressure. This was done by using a relation that I (Vardya 1984) had found earlier for O and B stars, using dimensional and physical arguments.

$$\dot{M} = A L^2 (R/M)^{3/2},$$

where L, R, and M are stellar luminosity, radius, and mass, and A a scaling constant. Therefore, we considered a relation between A or rather A/R^2 and $v \sin i$. Note that A may contain the dependerce of not only rotation but of other parameters as well, not considered so far, like magnetic field. This resulted in a single relation for all the 81 stars, with a high correlation coefficient The correlation improved markedly when the projected linear rotational velocity $v \sin i$ was replaced by the projected angular rotational velocity, $\Omega \sin i$. Thus, I showed for the first time, from observed data, that rotation definitely enhances the rate of mass loss, or more accurately, mass flux, confirming the theoretical expectations.

Now, the question is, is the amount of enhancement commensurate with theoretical predictions? I had found from observations that A/R^2 increases by about 2.5 dex for an increase of 1.5 dex in $v \sin i$ or 2.75 dex in $\Omega \sin i$. Theoretically, an increase by ~ 26% in $\dot{M}$ has been found as v goes from 0 to 350 km s^{-1} in a O5V star by Pauldrach, Puls & Kudritzki (1986); Poe & Friend have found for a O6ef star an enhancement of 62% in $\dot{M}$ as v varies from 125 to 400 km s^{-1} (with a magnetic field of 200 G), and an increase of 370% for a B1.5Ve star as v goes from 125 to 540 km s^{-1} (with a magnetic field of 50 G). Friend & Abbott (1986) have found that $\dot{M}$ (rotation)/ $\dot{M}$ (no-rotation) increases from 1 to 2 as v (rotation)/ v (break-up) goes from 0 to 0.8; however, their final conclusion, using observational data for O and B stars but excluding Be stars, is that there is currently no evidence for a dependence of the mass loss rates on rotational velocity, and the scatter in the observations is so large that it may not be possible to find such a correlation even if it exists. And not to have any conflict with their own conclusions, Friend & Abbot (1986) have made this cryptic statement: "A correlation between mass-loss rate and rotational velocity has been sought by Vardya (1985), but the evidence is very weak at best", without advancing any reason.

Nieuwenhuijzen & de Jager (1988) have discussed this difference between the theoretical conclusions and my (Vardya 1985) results, by considering 142 non-emission early type stars, but excluding Be and shell stars. According to them, the strong dependence that I found is a manifestation that both the rate of mass loss as well as $v \sin i$ is correlated to the luminosity of the star, thus giving an artificial correlation between M and $v \sin i$. Then they have fitted the data of $\dot{M}$ in terms of three variables, T_{eff}, L and $v \sin i$ by Chebychev polynomials of 39 coefficients, 20 independent of $v \sin i$ and 19 dependent on it, and have concluded that $\dot{M}$ depends only slightly on $v \sin i$. Critically examining their conclusions, we find that

(a) Nieuwenhuijzen & de Jager (1988) have excluded Be and shell stars, thus preventing proper randomization of $\sin i$.

(b) In the sample that I (Vardya 1985) had used, the luminosity L is not correlated with $v \sin i$, except in a limited region. In fact luminosity increases gradually with $v \sin i$, reaches a peak around 150 km s^{-1} and then decreases rather steeply. As a further check, a plot of log $\dot{M}$ vs log $v \sin i$ at a given luminosity log $L = 5.0 \pm 0.2$, containing 23 stars, covering a range of log M from -7.70 to -5.36 and of $v \sin i$ from 15 to 385 km s^{-1} shows no correlation. Furthermore, I have differenced out the effect of luminosity by considering A rather than $\dot{M}$.

(c) Chebychev polynomial fit of 39 coefficients—22 positive and 17 negative—with two-third coefficients of the same order of magnitude, may be a good numerical fit over a limited domain, but its utility ends there. Using it for physical interpretation is dangerous, to say the least. Besides, we are interested in v and not in $v \sin i$ dependence. And by such an accurate fit not only $\sin i$ has been incorporated but dependence of magnetic field as well.

(d) One should note that if the sample is restricted, *i.e.* limited to a small range in spectral class for example, the scaling or constant factor will absorb similar dependence, thus preventing an explicit manifestation of real dependence. In a similar way, when a large varied sample is fitted with an expression with a large number of coefficients, the real dependence will get absorbed in these coefficients and one will see only a kind of residual dependence.

(e) When Nieuwenhuijzen & de Jager (1988) considered Be and shell stars, which I have included in my analysis, they found that mass loss rate is larger by two order of magnitude from the equatorial areas relative to high latitude parts, which was similar to other stars.

(f) Theoretical results of Poe & Friend (1986) clearly show that the gradient of the increase of $\dot{M}$ as $v \sin i$ increases, increases sharply as the critical velocity is approached.

Recently Howarth & Prinja (1989) have considered 163 galactic O stars with $v \sin i$ between 5 to 435 km s^{-1}, log $\dot{M}$ between -4.6 to -7.8, log $L/L_\odot$ between 4.5 to 6.4, $M/M_\odot$ between 18 to 150, and $R/R_\odot$ between 5 to 36. They have found a change Δ log $M \cong 0.4$ when the velocity goes from slowest to the fastest rotation; however their expression is not valid for $v \sin i \leqslant 153$ km s^{-1}. They have also like us (Vardya (1985) considered a quantity similar to our A, in which the effect of luminosity and luminosity class is eliminated. Note that though they have taken a large number of stars, it is restricted in spectral class, $v \sin i$, log $\dot{M}$ and log $L/L_\odot$. Incidentally, the authors have claimed that the present result is the first reliable indication that such an effect actually exists in nature.

The question now is, is there really a discrepancy between results that I obtained and those of Nieuwenhuijzen & de Jager (1988) and Howarth & Prinja (1989) as well as theoretical results of Poe & Friend (1986), Friend & Abbott (1986) and others. Perhaps not. Apparent differences are due to looking at the problem differently, using different kinds of samples, and the problem posed by sin i in the observed data.

This is dedicated to Professor K. D. Abhyankar on the occasion of his 60th birthday.

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Discussion

Kameswara Rao : Would you comment on the rational for averaging your mass-loss rate over the surface or dividing the mass-loss rate divided by surface area?

Vardya : The main mechanism of mass loss is radiation pressure, which acts uniformaly over the surface. Rotational effects via centrifugal pressure, however, are not uniform over the surface. Therefore, averaging over surface works differently in the two cases. Hence, it is better to consider mass flux rather than mass loss itself.

Kameswara Rao : Can you comment on the rational of random distribution of i the inclination to the line-of-sight, particularly considering the OB stars which occur in O associations and in clusters which might have a definite orientation for their axis of rotation?

Vardya : Excess of low v stars over random distribution has been attributed to stars in associations or clusters having a given inclination. One hopes that if one takes a large enough sample from all directions, the sample will be reasonably randomized with respect to i. However, to get a complete unbiased fully randomized sample is a difficult proposition.

Rathnasree : Is a similar correlation seen in the rest of the HR diagram or is it confined to OB stars?

Vardya : No systematic study has been carried out for stars later than B spectral class As more and more rates of mass loss are becoming available for stars cooler than B, one can look into the effect of rotation of mass loss in the other parts of the H-R diagram
Periah : In the CAK theory we encounter negative velocity gradients, and this will not allow us to proceed any further. Is there any other way out of it?
Vardya : I do not know as I have not used the CAK theory in my work, nor have I looked into the details of its computational aspect
Periah : Is it not necessary to solve the equations of line transfer, mass momentum and energy consistently to obtain mass loss?
Vardya : Yes, but it is a difficult proposition, besides, it may not be necessary in all cases, considering the accuracy of the data