THE ROLE OF ROTATION IN LUMINOUS BLUE VARIABLES

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ABSTRACT: We demonstrate that differential rotation plays a significant role in the essential features of LBV's, among other types of objects.

1. INTRODUCTION

It has been known for some time that rotation is a common characteristic of stars in the upper-left-hand quadrant of the HR diagram. Rotational speeds display a bimodal distribution with maxima around 100 km/s and 300 km/s (Conti and Ebbets 1977; Useugi and Fukuda 1982).

However, this aspect has not received as much attention among those studying massive stars, partly because rotational effects are difficult to model and partly because there is still a considerable amount of confusion about their importance for massive stars (Chiosi and Maeder 1986). Classical studies of rotating stars have held that meridional circulation is too slow to cause significant change and that mean molecular weight gradients effectively prevent mixing (see Tassoul 1980 for a review). But it is becoming increasingly clear that there is evidence for mixing of material between the core and envelope of massive stars right across the HR diagram (see recent reviews in Nomoto 1988) including the example of SN1987A. It has also been known for some time that mass-loss rates in some types of massive stars such as WR stars, LBV's, and Be stars are much higher than predicted by radiatively driven wind theories. Be stars display different mass-loss rates between their polar and equatorial regions (see Abbott and Conti 1987, Slettebak and Snow 1987). Finally, pulsations in many early-type stars are believed to be non-radial and the precise driving mechanisms are still being discussed and debated (see Smith 1988 and Baade 1988 for recent reviews). We have advanced the hypothesis that rotation has a significant role to play in the structure and evolution of stars in the upper-left-hand quadrant of the HR diagram, as well as amongst intermediate-mass stars. We have tested this hypothesis in a number of cases and find that it is possible to understand these different features on the basis of a single hypothesis.

2. STRUCTURAL CHANGES DUE TO ROTATION

In studying the effects of stellar rotation, it has been customary to assume that stars either rotate like rigid bodies or that they

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possess rotation laws that are stable to begin with. When one does that in stellar models, they are found to possess smaller cores, lower effective and central temperatures, lower luminosities, higher central density and pressure and longer main sequence lifetimes (Bodenheimer 1971). There are slight quantitative differences between rigidly rotating models and those for which the specific angular momentum is proportional to the mass enclosed within a cylinder of radius ω. But there is no *a priori* reason why stars should obey either of these assumptions. It is equally reasonable to suppose that stars have differential rotation, as they are gas-masses and as viscosity and turbulence in them are anisotropic. The shear that is generated as a consequence brings the star into a state of dynamic equilibrium with some mean rotation rate for the core. Mixing between the core and envelope will be a natural consequence as is efficient meridional circulation and redistribution of angular momentum.

We have taken the latter stand and found that if the rotation law is specific-angular-momentum-conserving, then independently of whether or not the envelope is differentially rotating the core size is *smaller* if rigid rotation is imposed on the core, and the other consequences are similar to those found by Bodenheimer (1971). The model evolves as one of lower luminosity etc. until helium is completely burnt in the core (Sreenivasan and Narasimha 1986). But, if the core is presumed to be differentially rotating as well, following the same law: $\Omega\omega^2 =$ *constant*, one gets a larger core and the resulting mixing of material between the core and envelope makes the models bluer. This effect causes a widening of the main sequence, explains the observed blue/red supergiant ratios, and results in the appearance of CNO-processed products at the surface when mass-loss rates are significant. The change is brought about because the radiative gradient for differentially rotating models is *larger* and the adiabatic gradient is *smaller* than those of non-rotating models which are otherwise similar in properties. We wish to emphasize that this effect does *not* require very high initial rotational velocities. The higher the rotational speed, the more pronounced is the effect (Sreenivasan and Wilson 1988).

3. EVOLUTIONARY CHANGES DUE TO ROTATION

As a star evolves, the core shrinks and spins up while the surface spins down due to mass loss and the accompanying loss of surface angular momentum. This results in angular momentum transfer from the core to the envelope, increased shear turbulence, and more efficient meridional circulation. The mechanical energy flux generated by shear turbulence drives a non-thermal wind *in addition to* the radiatively driven wind. Thus, not only does differential rotation increase the mass-loss rate rate in early-type stars, but this increase increases with evolution. One can therefore understand the higher mass-loss rates of WR stars as well as LBV's. One can also understand the origin of circumstellar shells around these objects, because a larger rate of mass loss increasing with evolution produces a sweeping-up process as new wind catches up with material from an earlier wind, reminiscent of theories describing planetary nebula formation (Kahn 1983, Kwok 1983, Sreenivasan and Wilson 1986). Whether stars turn around in the HR diagram or not is strongly controlled by the mean molecular weight, the opacity in the outer layers, and the mass fraction of the helium core. Some stars do and some do not (Chiosi *et al.* 1978, Sreenivasan and Wilson 1988a,b). But the foregoing mechanism of the LBV stage is independent of the mass-loss effect. Hence one can understand LBV's which are *not blue*! Lately, we have found that differentially rotating models of massive stars are overstable for non-radial prograde sectorial g-modes. There are many such modes that are excited with frequencies close to each other. This leads to mode-coupling and the result is a long time modulation of a higher frequency oscillation with periods ranging from hours to fractions of a day. We believe that this affords a qualitative explanation of the pulsation properties of many B-type stars including LBV's. The pulsations are driven by differential rotation and they could explain the line-profile variability observed in 53-Persei-type objects (Smith 1988). In addition, variability in the winds of O stars has been inferred from P Cygni resonance line variations in the spectra (Prinja 1988) which correlate with their rotational velocities. Also, Moffat and his collaborators (1988) have observed variabilities in the winds of WR stars. Both these variabilities could be the results of interaction and instabilities in the winds caused by radiation pressure on the one hand and the non-thermal wind driven by mechanical energy flux due to shear-generated turbulence on the other. Our pulsation models are combined with evolutionary models of massive stars losing mass and angular momentum (Narasimha and Sreenivasan 1987) and the results are in qualitative agreement with those of Lee and Saio (1987,1988).

Since rotation is latitude-dependent, our models lead to the natural conclusion that mass-loss rates at equatorial regions are much higher than those in the polar regions. There is virtually no enhancement of the mass-loss rates due to radiatively driven winds in the polar regions and the enhancement is confined to an equatorial belt. This agrees with what is seen in Be-star winds. We have advanced a similar model for the pulsation of β Cephei stars, which are slow rotators, whereas Be stars are rapid rotators. We believe on the basis of our models that β Cephei stars are slowed down by mass loss and surface angular momentum loss, whereas the Be stars are those objects which have already generated circumstellar disks and hence are revealing interior layers exhibiting more rapid rotation assisted by angular momentum transfer from the spun-up shrunken cores.

Finally, we point out that our model leads to the conclusion that different initial rotation speeds on the zero-age main sequence result in differing rotational histories of massive ($>15\,M_\odot$) and intermediate-mass stars. We can thus understand the evolutionary features of massive stars displaying different mass-loss rates with other properties remaining much the same, or with higher effective temperatures that are now suspected for WR stars ($1.2\,M_\odot < M_\star < 9\,M_\odot$); the abundance anomalies of peculiar red giants amongst intermediate-mass stars as well as OB stars, yellow and red supergiants; the enigmatic evolutionary features and location of high-latitude F supergiants and the reasons for large-scale mixing in the progenitor of SN 1987A. We do not need to invoke problematic convective overshooting or excessive rotational speeds to cause the mixing (Sreenivasan and Wilson 1982, 1985abc, 1986, 1987). They simply become the result of including rotational effects.

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DISCUSSION

Langer: If a rotation law leads to appreciable convective core enlargement, this would resemble the effects of large convective overshooting. Don't you then run into the same kind of problem as in stellar models with large overshooting, *i.e.*, that very massive stars avoid the LBV phase after hydrogen burning and instead turn toward the blue and directly become Wolf-Rayet stars?

Sreenivasan: Only a relatively small amount of rotation is required to produce appreciable core growth; e.g., for a $70 M_\odot$ star, a value of $(v \sin i) \sim 150$ km/s increases the core size from about 50 $M_\odot$ to 56 $M_\odot$. The evolutionary tracks for such a population I model go to the red before turning blueward. So, what you are worried about does not happen. Only when unreasonably large overshoot is imposed and excessively large mass-loss rates (exceeding what is allowed by radiatively driven stellar winds) are invoked does that happen.

Vanbeveren: Do you think that rotation effects may be important in close binaries with periods, say, larger than ~ 4 days?

Sreenivasan: Yes!

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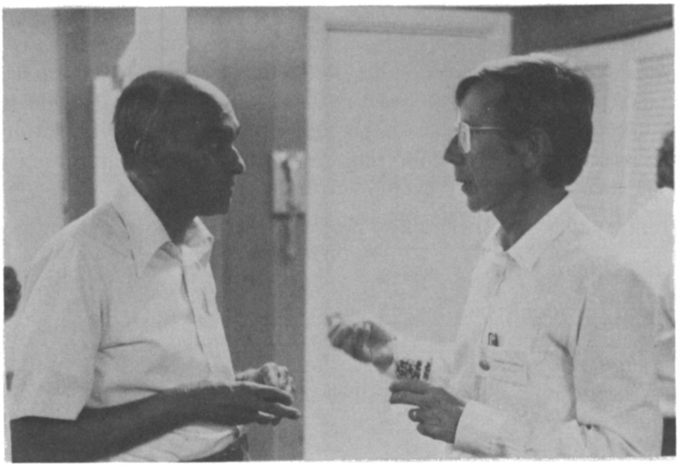

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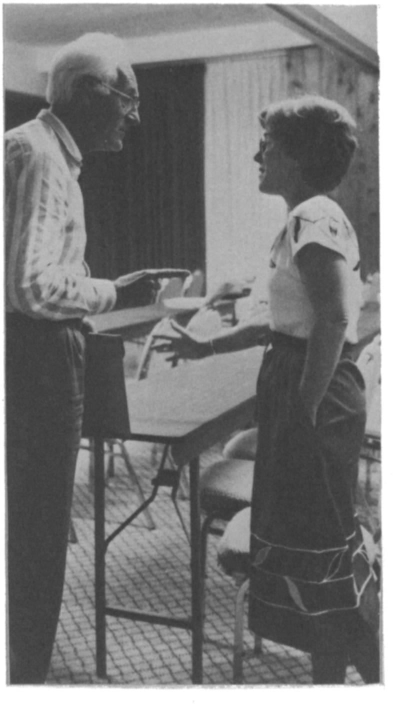

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