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ROTATIONAL EFFECTS IN SN 1987A

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Abstract

The possible evolutionary effects of rotation on the observational characteristics of SN 1987A and its progenitor Sk -69 202, are explored. If rotation is important, decrease in post main sequence luminosity and increase in rates of mass loss and mixing are likely. It is suggested that significant rotation, in addition to mass loss and low metallicity might explain the blue supergiant nature of precursor star. Observations of line profiles, polarisation and an asymmetric shape of the envelope are all consistent with moderate rotation.

INTRODUCTION

It is well known that massive stars have the highest surface rotational velocities, both on the main sequence and among supergiants, the B stars being the fastest rotators (Tassoul 1978). The progenitor of SN 1987A has been shown to be a star of 16-20 $M_{\odot}$ (Arnett 1987a; Hillebrandt et al. 1987; Shigeyama et al. 1987; Woosley et al. 1987). Hence it is natural to expect that rotation could have played a significant role in the evolution of the progenitor, and perhaps in the supernova event itself.

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Unfortunately, detailed numerical evolutionary models taking into account differential rotation in a fully self-consistent manner are not available at present. In particular, fully two dimensional models have not been attempted because of the tremendous computational difficulties. Essentially one dimensional approaches have been made which take into account some effects of rotation within evolutionary models that included semi-convection, mass loss and changes in the envelope composition (Sreenivasan and Wilson 1978; 1985). Evolutionary computations for relatively low mass stars from the early main sequence through early post main sequence phases have also been undertaken using an alternative set of approximations (Endal and Sofia 1976, 1978: Ramadurai and Wiita 1984; 1988), but our lack of understanding of the details of the physics of angular momentum transport renders all such models uncertain. Therefore in an attempt to make some general arguments concerning rotation in the late post main sequence phases of stars, we follow the semi analytical approach adopted by Wiita (1981), which extended an earlier analysis of Maeder (1974), to estimate the dominant effects of rotation for such stars. Of course, such simplified models are also very uncertain, but there is a growing list of observations that can probably be best understood if rotation is of some importance in SN 1987A, and our main purpose here is to encourage further investigations along these lines.

ESTIMATES OF ROTATIONAL EFFECTS ON LUMINOSITIES

The rotational effects are calculated for fixed core masses, as opposed to the fixed central densities used in Wiita (1981). The ratio of rotating to non-rotating luminosities is given by

$$(L_R/L_o)_\gamma = (1-X)^\delta, \qquad (1)$$

where

$$\delta = 4 + (n-4)/(b+1) \qquad (2)$$

if the dominant burning shell is radiative, and

$$\delta = b/(\Gamma_2-1) + n \qquad (3)$$

if it is convective, where the energy generation rate, ε, can be parametrised in terms of the density, ρ, and temperature, T, by

$$\varepsilon \propto \rho^b \ T^a \qquad (4)$$

The values for b and n are taken from Clayton (1968) and Γ_2 is the adiabatic index in the shell. The measure of mean rotational support at a given level in the star, χ, is given by

$$\chi = 2\,\Omega^2 r^3/(3GM_r), \tag{5}$$

and $\bar{\chi}$ and $\tilde{\chi}$ are the appropriate averages over the core and shell, respectively. The corresponding ratio for neutrino luminosities is

$$(L_R/L_o)_\nu = (1-\bar{\chi})^q\,(1-\tilde{\chi})^k, \tag{6}$$

with $q = 3(v-1)/(3\,\Gamma_2-4)$, and where the neutrino emissivity of the core, S_ν is taken as

$$S_\nu \propto \rho^v\ T^k \tag{7}$$

The values for v and k are taken from Schneider et al. (1987) and Weaver, et al. (1978).

The non-rotating models that provide approximate values for core mass, core and shell temperatures and densities are those of Weaver et al. (1978) with values for earlier evolutionary stages from Arnett (1974). The stellar evolution is extremely rapid for stars in the mass range relevant to the SN 1987A progenitor. Based on the most recent pre-explosion observations (West et al. 1987), it is inferred that SK -69° 202 was probably in either the carbon or oxygen burning phase and hence the estimates below are made for those phases.

Table 1 gives the estimates for the photon luminosity changes at different post-main sequence phases as a function of $\eta = \bar{\chi}/\tilde{\chi}$, the rotation parameter, and the value of $\bar{\chi}$. Solid body rotation through the core and burning shell corresponds to $\eta \simeq 0.25$, while $\eta \simeq 1.0$ indicates a reasonable degree of differential rotation, and $\eta = 4$ is equivalent to a very strong, probably maximal, differential rotation. The values of $\bar{\chi}$ investigated range from moderate rotation upto the maximum allowed by secular stability in the core. Case 1 corresponds to radiative shells, while Case 2 involves convective shells. Table 2 gives similar results for the neutrino luminosities, which are assumed to be dominated by emission from the core.

At this point an important caveat should be mentioned. Our analysis, starting from equation (1), is strictly valid only under the condition

Table 1. Ratios of Rotating to Nonrotating Photon Luminosities For 15$M_\odot$ Models

Phase	$\bar{\chi}$	Case 1			Case 2		
		η = 0.25	1.0	4.0	0.25	1.0	4.0
H burning	0.0187	5.27(-1)	8.66(-1)	9.62(-1)	2.16(-1)	6.89(-1)	9.12(-1)
shell	0.0935	2.12(-2)	4.46(-1)	8.23(-1)	9.83(-5)	1.45(-1)	6.28(-1)
	0.1870	1.19(-5)	1.82(-1)	6.75(-1)	1.6(-12)	1.69(-2)	3.90(-1)
He burning	0.0187	6.16(-1)	8.52(-1)	9.61(-1)	1.27(-1)	6.06(-1)	8.83(-1)
shell	0.0935	1.86(-2)	4.34(-1)	8.18(-1)	4.07(-6)	7.42(-2)	5.34(-1)
	0.1870	8.12(-6)	1.72(-1)	6.64(-1)	1.4(-16)	4.15(-3)	2.80(-1)
C burning	0.0187	6.42(-1)	8.98(-1)	9.74(-1)	3.74(-1)	7.88(-1)	9.42(-1)
shell	0.0935	6.89(-2)	5.71(-1)	8.74(-1)	2.67(-3)	2.89(-1)	7.41(-1)
	0.1870	3.82(-4)	3.07(-1)	7.61(-1)	2.68(-8)	7.29(-2)	5.46(-1)
O burning	0.0187	3.32(-1)	7.65(-1)	9.36(-1)	5.13(-2)	4.86(-1)	8.36(-1)
shell	0.0935	1.29(-3)	2.48(-1)	7.15(-1)	1.69(-8)	2.35(-2)	4.05(-1)
	0.1870	3.16(-9)	5.29(-2)	5.07(-1)	1.4(-23)	3.68(-4)	1.61(-1)
Si burning	0.0187	3.04(-1)	7.49(-1)	9.31(-1)	4.13(-2)	4.61(-1)	8.25(-1)
shell	0.0935	7.72(-4)	2.23(-1)	6.96(-1)	4.57(-9)	1.79(-2)	3.79(-1)
(25 $M_\odot$)	0.1870	6.9(-10)	4.21(-2)	4.81(-1)	2.9(-25)	2.06(-4)	1.40(-1)

Table 2. Ratios of Rotating to Nonrotating Neutrino Luminosities For 15$M_\odot$ Models

$\bar{\chi}$	Phase	η = 0.25	1.0	4.0	Phase	η = 0.25	1.0	4.0
0.0187	He core	7.40(-1)	8.53(-1)	8.83(-1)	C core	4.33(-1)	8.52(-1)	1.00
0.0935		1.80(-1)	4.38(-1)	5.24(-1)		6.15(-3)	4.34(-1)	1.02
0.1870		1.06(-2)	1.76(-1)	2.57(-1)		2.43(-7)	1.72(-1)	1.07
0.0187	O core	7.42(-1)	1.48	1.10	Fe core	4.59(-1)	9.26(-1)	1.10
0.0935		9.00(-3)	6.85(-1)	1.64		8.16(-3)	6.69(-1)	1.62
0.1870		5.03(-7)	4.50(-1)	2.90		3.78(-7)	4.28(-1)	2.84

that there is no significant mass loss. However, it is very likely that the dominant reason for the small size of the progenitor is that it underwent significant mass loss (e.g., Hillebrandt et al.1987). Recent gamma ray observations from Antartica as well as earlier X-ray observations have provided more support for models incorporating mass loss (J.Trombka, private communication). Thus, an improved model would modify (1) so as to take $\dot{M}$, the mass loss rate into account. Because the loss of mass also implies a loss of angular momentum, the assumption of local conservation of angular momentum during contraction is no longer valid. We have tried several ways of estimating this effect, although none of them is fully satisfactory. The rough result is that the combined losses of envelope mass and angular momentum probably leave equation (10) of Maeder's (1974) analysis unchanged, upon which this work is based.

Tables 1 and 2 indicate that for any reasonable angular momentum distribution in the star, the dominant effect of rotation on stellar evolution is to decrease the photon luminosities of the star at every epoch, thereby increasing the lifetimes of these stages. This is in accord with earlier discussions of the photon luminosities for stars with rigidly rotating cores or with stable differential rotation burning H or He (Bodenheimer 1971). However, when the differential rotation is strong enough, corresponding to the preservation of constant specific angular momentum, then the core size can grow substantially thanks to strong mixing; this can actually increase the luminosity and corresponds to performing the above analysis for constant $\mathcal{J}_c$ instead of constant M_c (Maeder 1974; Wiita 1981). Nonetheless, the concomitant rise in available fuel under such circumstances also increases the lifetimes of the H and He burning phases. This significant uncertainty in the outcome shows that the unknown rotational history of the star can play a very important role and stresses the need for an improved treatment of this question.

Retaining our assumption that constant M_c is a better approximation, we find that fairly rapid rotation in the core reduces its luminosity significantly without much altering its radius. But if the envelope is relatively slowly rotating, so that the gravitational potential is not significantly changed, then the radius of the star must become smaller. However, it should be borne in mind that the adjustment of the envelope takes place on a thermal timescale which is long compared to the carbon, oxygen and silicon burning timescales. Hence the putative differential rotation induced decrease in radius, relevant to Sk -69° 202, is probably mainly attributable to the helium burning stages.

Still, since the photon luminosities decrease quite rapidly with increasing rotation, in this case it is possible to set a rough upper limit to the amount of rotation in the central regions of the star. Measurements of the brightness of Sk -69° 202 (West et al. 1987) are consistent with models with a (non-rotating) masses between $\sim$ 15 and $\sim$ 25 $M_\odot$, which vary in their pre-supernova luminosity by a factor of about four (Arnett 1987a; Hillebrandt et al. 1987; Woosely, Pinto and Ensman 1988). The small radius of this star provides an additional constraint and we can conclude that $\bar{X}$ should not exceed more than about 0.03 for n = 0.25 or about 0.10 for n = 1, which are about 16% or 54% respectively, of the maximum allowed by secular stability (Wiita 1981). Very strong differential rotation within the core, with its corresponding rise in luminosity, makes it harder to fit the properties of the precursor. However the likelihood is that much of the reduction in radius of the star was due to mass loss, and this, if quantifiable, could eventually tighten the limits on the star's rotational history.

OTHER EFFECTS OF ROTATION

Rotation increases the mass loss rate, as has been shown by Sreenivasan and Wilson (1985). There are several reasons for this: eg. the reduction of effective gravity, increased turbulence due both to core spin-up through evolution and envelope spin-down explicitly due to the mass loss. As mentioned above, essentially all of the non-rotating models evolved to account for SN 1987A demand a substantial amount of mass loss (Nomoto 1988; Woosley 1988; Arnett 1988). Thus it is certainly reasonable to believe that the rapid mass loss required of the progenitor star was at least assisted by rotation during its main sequence and helium burning stages.

Further, most such models pass through a red supergiant stage before entering the blue supergiant phase. During this period there should be some mixing of the CNO processed material. The spectrum of the supernova indicated the presence of such material early on (Ashoka et al. 1987; Wamstaker et al. 1987; Kirshner 1988; Wampler 1988). Because rotation is expected to enhance the mixing of this CNO processed material (Sreenivasan and Wilson 1978;

1985), this abundance data is also consistent with rotation playing a role, although it does not require it to do so. This point has recently been made independently by Weiss, Hillebrandt and Truran (1988).

More evidence that rotation probably is important can be inferred from the fact that the spectral features at H_α He I (λ6678) were both double peaked, with separations of ~ 1400 and ~ 850 Km. sec^{-1}, respectively (Ashoka et al. 1987), although again other interpretations are possible. Further support comes from various line profiles in the infrared. Additional indirect support comes from the polarisation of the radiation from the Supernova (Schwarz and Mundt 1987; Clocchiatti and Marraco 1988) which could be most simply explained if there was an asymmetry in the envelope caused by rotation.

Limits on the influence of rotation can be adduced from the neutrino burst observations from SN 1987A (Arnett 1987b). If rotation were to play a very strong role in the core of the supernova then the excellent fit of the observed neutrino spectrum and time delays to a standard non-rotating collapse scenario (Burrows and Lattimer 1987) would be unlikely. Early on it was suggested that some of the peculiarities of the light curve could be explained if a fast pulsar was making an important contribution to the energetics (Ostriker 1987). However, the excellent agreement with the radioactivity powered model for the later light curve rules out any significant pulsar contribution and implies that rotation in the core was probably not very important (Arnett 1987b).

Although it is extremely difficult to make more quantitative statement without performing currently impossible fully two dimensional evolutionary models, we conclude that the evidence in favour of rotation having played a significant, although not dominant, role in the evolution of the progenitor of SN 1987A is reasonably strong. The following scenario emerges from the arguments summarized above: rotation may have played an important part during the mainsequence and early post-mainsequence phases of the star, encouraging mixing, increasing mass loss and helping to produce a smaller pre-supernova star. But it is likely that a significant amount of angular momentum was eventually transferred to the envelope so that the collapse to a neutron star was not greatly affected and a very fast pulsar did not form. The expanding envelope may be showing the effects of rotation in the forms of split line profiles and polarisation.

Probably the strongest test of the relevance of rotation can be made in the future, for if it is indeed of real importance, the remnant is more likely to evolve into an axisymmetric, rather than spherically symmetric, shape. As this paper is being prepared we were pleased to hear that this prediction may already have been borne out by speckle interferometric measurements which indicate that the shell has developed a noticeable asymmetry in the form of an elongation along one axis (Karovska et al. 1988), which is apparently related to the polarisation axis (H. McAlister 1988, private communication).

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