THE KINEMATICS OF PECULIAR RED GIANTS

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Abstract. The ages, masses and evolutionary state of peculiar red giants are discussed on the basis of kinematic and other data.

INTRODUCTION

In discussing the kinematics of the peculiar red giants, and the contribution that the kinematics make to our understanding of the evolution of these stars it is convenient to deal first with those objects whose peculiarities are believed to arise from evolutionary processes in single stars and then those (e.g. BaII stars, CH stars) whose peculiarities seem related to their presence in binary systems. This division into single and double systems is as yet only tentative (see the recent discussion of the probable binary nature of some S type stars (Jorissen & Mayor 1988). In addition, some peculiarities may simply reflect unusual abundances in the material from which the stars formed, as has been suggested as one possible explanation for some of the peculiar red giants in the globular cluster Omega Centauri (cf. Lloyd Evans 1983).

An earlier review of this general topic was published by Catchpole & Feast (1985).

S STARS, C STARS, MIRAS

Overall, mean, results for the kinematics of C, S and SC stars in the general field can be obtained in a straightforward way from radial velocities. Table 1 shows estimates of the total velocity dispersion, $\sigma_T = (\sigma_U{}^2+\sigma_V{}^2+\sigma_W{}^2)^{1/2}$, for various groups of objects. For the S, Se and SC stars these values have been obtained from the unpublished data of Catchpole (cf. Catchpole & Feast 1985). The C star data is from Dean (1976). Note that the stars with emission lines are generally Mira type variables. The relation between σ_T and age deduced by Wielen (1977) from stars of known age in the solar neighbourhood can then be used to estimate rough ages and these are shown for some of the groups in the table. Estimates of the corresponding initial masses are also given. These were derived from Buzzoni's interpolation formula for the Yale isochrones assuming that the initial abundances are approximately solar (Iben & Renzini 1983, equation 2). The values of σ_T for the Me type Mira variables, which are listed for comparison with the S and C stars, were obtained from the data in Feast *et al.* (1972).

The results in Table 1 indicate that the bulk of the S and C type stars are low mass objects of intermediate age. There is some indication from the kinematics that the C stars as a group may be younger and (initially) more massive than the S and SC stars. It would be desirable to confirm this result from larger samples of stars with each sample analysed using identical methods. Dean (1976) omitted from his sample of C stars all CH stars, and all stars with large radial velocities ($|\rho|$ >100 kms^{-1}) on the grounds that the latter stars were CH-star candidates. This exclusion may be reasonable in view of the fact that CH stars are likely to be a quite different type of object from other C stars. The possible exclusion of some high velocity non-CH stars in this process might be feared to have artificially reduced the velocity dispersion of "true" C stars. However it can hardly have affected the comparison with the S and SC stars in Table 1 since in fact none of the S stars and only one of the SC stars, in the samples used, had $|\rho|$ >100 kms^{-1} (the SC star was Case 598 with a velocity, corrected for local solar motion, of -101 kms^{-1}). An uncertainty in the comparison is introduced by the fact that some of the C, S and SC stars used are probably sufficiently distant for the effects of galactic rotation to be important, so that the results depend somewhat on the adopted absolute magnitudes.

TABLE 1

The velocity dispersions of peculiar red giants and Mira variables

Type	Number of stars	σ_T kms^{-1}	Age	$M_i/M_\odot$
1(a) S and C Stars				
S	124	55	~5 Gyr	~1.3
Se*	29	61		
SC	30	66		
C	427	37	~2 Gyr	~1.6
C type Miras	36	<41		
1(b) M-type Miras				
P < 145 days	22	81		
145 < P < 200	46	180		
200 < P < 250	71	101		
250 < P < 300	77	88		
300 < P < 350	83	69		
350 < P < 410	54	58		
P > 410 days	35	50		

* These will be mainly S type Miras.

A fuller interpretation of these results is complicated by the fact that there may be a spread in ages and initial masses within the groups of S, C and SC stars in Table 1. This seems likely for C stars since such stars are found in Magellanic Cloud clusters with ages ranging from ~10^9 to ~10^{10} years (cf. Frogel & Blanco 1984; Cohen 1982; Lloyd Evans 1984).

Another group of objects which indicates a spread of ages amongst the PRGs is the Mira variables. It is now clear that we must include Mira variables, or at least the more luminous ones, amongst the PRGs. This was long suspected to be the case, not only from the occurrence of S and C type Miras but also from the frequent occurrence of MS stars amongst Miras. These conclusions have been strongly reinforced by the recent work of Little et al. (1987) who find that most (M type) Miras with periods greater than about 300 days (M_{Bol} = -4.6 on the Mira period - luminosity relation) have TcI lines which show that there has been a recent dredge-up phase. The M type Miras are not a kinematically homogeneous group. They show a dependence of both velocity dispersion (cf. Table 1) and asymmetrical drift on period (Feast 1963; Feast et al. 1972). These kinematic results indicate that the longer period (~400 day) M type Miras are of intermediate age (~5 Gyr) and of somewhat over one solar (initial) mass, the shorter period (~200 day) M type Miras belong to an older population (>10 Gyr) (cf. Feast & Whitelock 1987).

It is clear from the above discussion that in order to make full use of the kinematic information one requires some parameter which will enable one to divide the spectroscopic groups (C,S,SC etc) into subgroups which are homogeneous as regards age and initial mass. The evidence indicates that in the case of the M type Miras, the period can be used as this parameter. The period has a further importance for Miras because of the existence of an infrared and bolometric, period-luminosity relation. This relation has been best demonstrated for the Miras in the Large Magellanic Cloud (cf. Glass et al. 1987) but is also shown by the relatively few known SMC Miras (cf. Lloyd Evans et al. 1988; Feast 1988a), by Miras in globular clusters (Menzies & Whitelock 1985; Feast 1987) and by Miras in the galactic bulge (Glass & Feast 1982; Feast 1986). At K (2.2μm), the same relation fits Miras of spectral types M, C and S rather well. In M_{Bol} the M and S type Miras in the LMC fall on the same relation whereas the C type Miras apparently fall ~0.25 mag fainter than the other types at a given period (See Glass et al. 1987). It is not yet entirely clear whether this displacement is real or an artifact of the very different energy distributions of the C and M type stars which could lead to spurious systematic differences when deriving M_{Bol} by integrating multicolour, broad-band photometry. In the following we refer mainly to the PL relation shown by M and S type Miras.

By combining the ages (or initial masses) of M type Miras as a function of period, derived from the kinematics, with the corresponding PL luminosities we can compare the results with predictions for the top part of the AGB which can be obtained, e.g. from figure 2 of Iben and Renzini (1983) (cf. Feast & Whitelock 1987). With an age of ~5 Gyr and an M_{Bol} of -4.7 at a period of 400 days (and corresponding pairs of values at other periods) one finds that the Miras lie ~0.5 to 1.0 magnitudes brighter, at a given age, than the predicted values for the start of thermal pulsing on the AGB and that in fact they are close to the locus of the highest luminosity predicted on the AGB if the mass loss parameter $\eta \sim 2/3$.

The narrowness of the PL relation (σ = 0.16 mag in M_{Bol}) taken together with the fact that Miras in any one globular cluster are closely clustered at the top of the AGB, and the results just discussed, suggest that M type Miras are confined to a very narrow luminosity range at each age/initial-mass. Thus one concludes that they lie distinctly above the luminosity at which thermal pulsing begins. Evidence on the luminosities of small amplitude variables in globular clusters (Whitelock 1986; see also Feast 1988b) tentatively suggests that these stars may populate the region between the start of thermal pulsing and the AGB tip occupied by the Miras.

As already indicated the work of Little et al. (1987) has shown that technetium is not present in the short period Miras, indicating that dredge-up of s-process elements is not taking place in these stars. This is in broad agreement with theoretical predictions that such dredge-up will be absent in low mass objects (cf. Iben and Renzini 1983).

There is a general tendency for the C type Miras to have longer mean periods in the LMC (cf. Glass et al. 1987) and in the general solar neighbourhood (cf. Merrill 1960) than the M type Miras. However, the most striking feature of these distributions is the substantial overlap in periods between the two classes. This overlap in periods and the absence of C type Miras in the galactic bulge (Blanco et al. 1984) seem potentially important clues for our understanding of PRG's. There are a number of possible alternative explanations of these results, some of which are discussed below.

Suppose the similarity of the PL relations for M and C type Miras is taken to indicate similar current and initial masses at a given period for stars in these two groups. In that case there are at least two possibilities. (1) At a given initial mass there is a range in [Fe/H] values. The more metal-rich stars do not evolve into C stars (cf. Iben & Renzini 1983). This explanation requires that there is a significant spread in metal abundance at a given age in the solar neighbourhood and in the Magellanic Clouds. The relatively metal poor component would be missing in the galactic bulge. (2) An alternative is suggested by the result, discussed above, that Miras (at least M type Miras) occupy a narrow range of luminosities (at a given age) well above the luminosity at which thermal pulsing on the AGB begins. Theory predicts (cf. Iben & Renzini 1983) that a star will decrease in luminosity by 0.5 - 1.0 magnitudes (bolometric) between thermal pulses (the exact amount depending on the mass). The possibility then exists that a star will only enter the Mira stage at a bright part in the thermal pulse cycle, dropping back to lower luminosities and small amplitude pulsation (or constancy) between thermal pulses. A star would then enter the Mira phase several times but each time with a higher C/O ratio and a higher abundance of s-process elements due to dredge-up. The attraction of this scheme over one in which a star evolves from an M to a C type Mira entirely within the Mira phase, is that the occurrence of low amplitude (or constant) C (and S) stars can be naturally accommodated into the scheme. The second of these two schemes does not require a spread in metal abundance in any one environment.

An entirely different possibility is tentatively suggested by the data in Table 1. These show that the velocity dispersion of C type Miras is smaller than that of even the longer period groups of (optical) M type Miras. It would be particularly important to confirm this result since it suggests that the C type Miras belong to a younger, higher initial mass, population than even the longer period M type Miras. The current masses are not necessarily different at a given period since the C type Miras may have evolved from stars which underwent heavy mass loss. There is evidence (Feast 1985) that the very long period (600-2000 day) OH/IR stars extend the M type Mira sequence to higher luminosities and presumably higher initial masses. Thus the C type Miras could, in this scheme, evolve from the OH/IR stars or from objects of somewhat larger initial mass. Further kinematic work should enable us to clarify the evolutionary connection between these different groups of stars.

Whilst the S type stars fit, at least qualitatively, into the picture of AGB dredge-up, there are some apparent anomalies. The outstanding kinematic puzzle is probably NT Tel, an Se Mira at $\ell = 347^\circ.6$ $b = -25^\circ.4$ with a radial velocity of +325 kms^{-1} and a period of 252 days (see Andrews 1975 and also Catchpole & Feast 1985). No other S star is known with a velocity, $|\rho| > 100$ kms^{-1}. Most observational and theoretical evidence leads us to expect that single PRGs will be absent from the halo population to which this star presumably belongs. One possibility is that it is in a binary system in which mass exchange has taken place (e.g. it is an evolved BaII star). Alternatively it could perhaps have formed from s-process rich material (as mentioned earlier this is one possible explanation for some PRGs in Omega Centauri).

Further work is required on the four S type stars in the region of the Eta Carinae complex to decide definitely on their membership of the complex. This grouping is very young (it contains early O type stars) and S type stars would not be expected theoretically. (See the discussion in Catchpole & Feast 1985).

It has been recognized for sometime that because carbon stars can be detected out to large distances they are of considerable potential importance for the study of the kinematics not only of our own galaxy but also of the Magellanic Clouds and of other galaxies (c.f. Richer 1988). Many carbon stars are periodic or quasi-periodic variables. However we can only expect the PL relation discussed above to hold if we restrict the sample studied to Mira type variables (note that the M type low amplitude variables in globular clusters show a PL relation of much lower slope (Whitelock 1986 see also Feast 1988b). It is not surprising therefore that Claussen et al. (1987) find no evidence for a period-luminosity relation for a sample of galactic C type variables, many of which are non-Miras.

Schechter et al. (1988) have recently carried out an extensive radial velocity study of distant C stars in our galaxy. A considerable range in absolute magnitudes is expected amongst these stars since in the Magellanic Clouds the C stars range in M_K (the absolute magnitude at 2.2μm) from -7 to -9. Thus in analysing the data Schechter et al. have to allow for significant Malmquist-type bias. Using their analysis and adopting $M_K = -7.9$ (± 0.6), a mean value derived from the Magellanic Clouds, one can derive a value for the distance to the galactic centre $R_0 = 8.4 \pm 0.6$ kpc and an Oort constant $A = 14.8 \pm 1.4$ kms^{-1} kpc^{-1}. These values agree quite well with values recently derived from a study of the kinematics of Cepheids ($R_0 = 7.8 \pm 0.7$ kpc, $A = 14.6 \pm 1.8$ kms^{-1} kpc^{-1}) (Caldwell & Coulson 1987).

BaII STARS, CH STARS

The evidence is now strong that BaII and CH stars are members of binary systems (cf. McClure 1988). The BaII stars can be divided into a number of spectroscopic subgroups (BaII weak, BaII strong, metal weak BaII star). As discussed by, e.g. Catchpole et al. (1977) and Catchpole & Feast (1985) these subgroups have different kinematic properties (cf. Table 2) indicating that the group as a whole is a heterogeneous one with a range of ages and absolute magnitudes. The CH stars are particularly interesting from the kinematic point of view because they seem to define a rather pure halo population. Several of the CH stars, including some towards the galactic poles, have radial velocities (without regard to sign) greater than 200 kms^{-1} and one, the Fehrenbach-Duflot star in the direction of the LMC, has a radial velocity of +440 kms^{-1} (Fehrenbach & Duflot 1981). Table 2 lists the galactic components of the velocity dispersions as well as the total dispersions for CH stars and some other groups. Hartwick & Cowley (1985) have drawn attention to the fact that whilst the total (or one co-ordinate mean) velocity dispersions of CH stars, metal poor giants and globular clusters are about the same, the ratio of the axes of the velocity ellipsoids are possibly different. Thus σ_U/σ_V may be different for the CH stars and for the metal-poor giants (cf. Table 2). Hartwick & Cowley suggest that this may indicate different kinematic histories for the various groups. Improved statistics are necessary to test this possibility. Mould *et al.* (1985) note that their results are suggestive of a velocity ellipsoid whose major axis points always to the galactic centre rather than being parallel to the galactic plane.

The CH stars obviously have an important role to play in the study of the galactic halo. There is a drawback in that they cover a rather wide range in absolute magnitudes ($M_V \sim 0$ to -3, even excluding the subdwarf CH stars) (cf. Catchpole & Feast 1985; Hartwick & Cowley 1985; Bond 1974 and references therein). Though this can possibly be overcome using a colour-luminosity relation (cf. Hartwick & Cowley 1985). There is also some difficulty in defining the group precisely. For instance the carbon star V CrB ($\rho = -115$ kms^{-1} b = +51°) is sometimes considered a CH star and sometimes not. It seems possible that the CH stars could in fact form a continuous sequence of kinematic groups with the various subgroups of BaII stars (cf. Table 2). Indeed a star such as HD 36598 which has been classified both as a BaII (with strong CN and CH (MacConnell *et al.* 1972, Catchpole *et al.* 1977) and as a carbon star (Stephenson 1973; Sanduleak & Davis Philip 1977) might perhaps be as well classified with the CH stars, and the star HD 115444, which is classified as a BaII, has [Fe/H] = -2.95 (Griffin *et al.* 1982) and is presumably a member of the halo.

Hartwick & Cowley (1985) find the remarkable result that the local space density of CH stars must be high (5.6×10^{-9} pc^{-3}). They point out that this is only one third of the local space density of metal

TABLE 2

The velocity dispersions of CH stars, BaII and some other objects

Type	Ref.	Number	σ_U	σ_V	σ_W	σ_T
				kms^{-1}		
CH stars	(1)	51	$\sqrt{-2966 \pm 48}$	161±24	125±18	196
CH stars	(2)	9			101±24	
Metal Poor Giants	(3)	52	141±16	106±23	56±30	185
Globular Clusters*	(4)					204
BaII weak stars*	(5)	25				29
BaII strong stars*	(5)	40				43
Metal weak BaII stars*	(5)	27				57

* $\sigma_T = \sqrt{3}$ (dispersion in radial velocity)

(1) Hartwick & Cowley 1985 (2) Mould *et al.* 1985 (3) Hartwick 1983
(4) Frenk & White 1980 (5) Catchpole *et al.* 1977.

poor giants. It is not clear that this is consistent with the relatively few CH stars in globular clusters. Perhaps this is an indication that only a limited proportion of the CH stars belong to a globular cluster-like population. If Harwick & Cowley's conclusions are even approximately correct they show that large numbers of CH stars remain to be discovered. They predict approximately one CH star per square degree brighter than V = 15 at the galactic poles. In that case one might expect a significant number of galactic CH stars to occur in the objective-prism surveys of the Magellanic Clouds for carbon stars, especially ones such as the LMC survey by Sanduleak & Davis Philip (1977) which was carried out in the blue region and therefore found preferentially the hotter carbon stars. This survey in which 474 carbon stars were found, covered about 72 square degrees and went down to V = 16 with all except three stars of V > 14 or fainter. The two brightest are the BaII/CH star HD 36598 mentioned above (V = 8.5, ρ = +48 kms^{-1}) and HD 269343 (V = 12) which has a very similar spectrum and ρ = +226 kms^{-1} (Feast & Spencer Jones, unpublished). This velocity is within 10 kms^{-1} of that of the LMC in this direction, but it seems unlikely that it is a member since its brightness would then be M_V = -6.5. Presumably it is a member of the halo of our galaxy. At M_V = 16 an object with a CH-like spectrum could conceivably be a low luminosity CH star in the outer halo of our galaxy or a high luminosity CH star in the LMC. A colour-absolute magnitude relation might be used to distinguish between these possibilities. It should be noticed that even a survey like the Sanduleak-Davis Philip one will not uncover all the CH stars. Their survey missed the high velocity CH star found by Fehrenbach & Duflot (1981), presumably because it has very weak C_2 bands. The Case survey of the Northern Galactic Cap (cf. Report of Warner and Swasey Obs. Bull AAS 20, 136, 1988) should contain many new CH stars.

CONCLUSIONS

Kinematic studies have made major contributions to our understanding of peculiar red giant stars. However a number of the results discussed in this review are still quite tentative. A major extention of kinematic studies of these stars in our own and other galaxies would greatly help in defining more precisely the ages, masses and evolutionary state of these objects.

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