Binary S and MS Stars

Hollis R. Johnson
Astronomy Department SW 319, Indiana University
Bloomington, Indiana 47405 U.S.A.

ABSTRACT. We assemble and discuss evidence for binarity in S and MS stars – stars that are enriched in s-process elements. A popular view is that Tc-deficient S and MS stars are not thermally pulsing AGB stars but are mass-transfer binaries. We describe several methods used to test this hypothesis through a search for the putative white-dwarf companion: (1) periodic radial velocity variations, (2) direct observation of the hot companions with IUE, (3) evidence of a hot gas cloud (hotter than a chromosphere) in the system, and (4) evidence of circumstellar dust as revealed through infrared radiation. Results of these methods are compared. All evidence supports the idea that Tc-deficient S and MS stars are mass-transfer binaries, and a large fraction appear to be interactive.

Introduction

Interest in binarity among the S and MS stars (lumped together here as S stars) extends far beyond the obvious consideration that there are many binaries among their immediate ancestors – the K, M giants. Our story properly begins with the discovery of lines of the unstable element Tc in the spectra of certain S stars (Merrill 1952), which demonstrated the reality of current mixing of nuclearly processed material to the surface. Later surveys demonstrated that such mixing processes occur in most or all AGB stars, and theorists have worked hard to re-produce these observations by mixing (called the third dredge up), for it requires special conditions that strain current theories.

On the other hand, it was noted some years ago (at least as early as Scalo and Miller 1981) that 9 of 30 non-mira S stars examined to that time did not have Tc. This figure is revised to 38% in more recent surveys (Little, Little-Marinen, and Bauer 1987 (LLB); Smith and Lambert 1988), and the lack of Tc poses a serious challenge to the usual dredge up scenario.

Many of the abundance peculiarities in spectra of stars in the sequence M-MS-S-C (enhancement of ^{12}C and s-process elements) are understood as products of the third dredge up accompanying thermal pulses (helium shell flashes) in low-mass stars. That most stars in the mass range 1-6 $M_{\odot}$ (the upper limit being slightly uncertain) follow

Y. Kondo et al. (eds.), Evolutionary Processes in Interacting Binary Stars, 157–166.

this scenario and proceed through the sequence M-S-C has been repeatedly emphasized from studies of the Magellanic clouds (Bessell, Wood, and Lloyd Evans 1983; Lloyd Evans 1984), from theoretical evolutionary calculations (cf. Iben and Renzini 1983; Wood 1985; Iben 1987; Lattanzio 1989), and from detailed investigations of the chemical composition of these objects (Smith and Lambert 1985, 1986, 1988, 1990; Lambert 1991). Although some uncertainties remain, such as our lack of understanding of the physics of convection (Lattanzio 1989) and of the difficulty of finding intermediate-mass stars that use the neutron source ^{22}Ne (Lambert 1991), the broad outline of the scenario seems clear.

Certain S stars, however, present the problem that their luminosities appear to be too low for thermal pulsing to have begun (from theoretical considerations), yet they show definite enrichment of s-process elements and sometimes carbon. Among such anomalies are the Ba stars and CH stars. Furthermore, as noted above, a large fraction of the bright S stars surveyed so far - 22 out of 58 – do not show Tc lines in their spectra (LLB; Smith and Lambert 1988). Yet once the third dredge up begins, Tc is expected to be continuously present on the stellar surface, and its absence in many S and MS stars forces us to seek explanations elsewhere.

The discovery that all Ba stars are binaries (McClure, Fletcher, and Nemec 1980) opened the way for an attractive explanation of the puzzle by the following scenario. Imagine the evolution of a binary system in which the two stars (X,Y) have slightly different masses. While the less massive star (Y) is still on the main sequence, the more massive star (X), evolving more rapidly, becomes a red giant and then an AGB star. Star (X) begins thermal pulses, dredges enriched material (enriched in ^{12}C and s-process elements) to its surface, and then sheds its entire envelope in the usual red-giant wind. Some of the material thrown off by the giant is captured by the main-sequence companion (Y), changing its surface composition. After losing its outer envelope, star (X) rapidly evolves through the planetary-nebula and post-planetary-nebula stages, fades rapidly, and begins its slow cooling as a white dwarf (WD). Much later, star Y (now the more massive of the two) evolves off the main sequence and becomes a red giant itself. Because its surface layers are enhanced in carbon and s-process elements, it appears as an AGB star, but it is actually a masquerader whose chemical peculiarities are due to mass transferred from its companion (X, now a WD). Later studies confirm that all Ba stars are binaries (Jorissen and Mayor 1988) and that the companion is a WD (McClure and Woodsworth 1991). Are Tc-deficient (here called (no-Tc) S stars also binaries? That is, are (no-Tc) S stars evolved Ba stars? It is perhaps noteworthy that the space density of (no-Tc) S stars, relative to M giants, is roughly the same as the space density of Ba stars relative to K giants (Smith and Lambert 1988).

A vital link in considerations of binarity is the element Tc (cf. Little-Marenin and Little 1979; Peery 1986; Smith and Lambert 1988; LLB; Little-Marenin 1989; Kipper 1991). Its uniquely valuable characteristic is the fact of its having no stable isotope; the half life of the only s-process isotope (^{99}Tc) is about 200,000 years. Consequently, Tc is absent in normal stars. In AGB stars, Tc is produced along with other s-process elements by slow neutron capture and is then dredged to the surface. Since the AGB lifetime of stars is only a few million years (a few half lives of Tc), some surface Tc would be expected to survive throughout the AGB lifetime. Furthermore, the time interval between dredge-up episodes – something like 50-100,000 years – is shorter than the half life for decay, so that the Tc on the surface is continually refreshed. That mira variable stars of all spectral types with P > 300 days show Tc lines in their spectra (LLB) confirm this theoretical idea.

If the stellar surface were contaminated by matter captured from an AGB companion, however, the Tc would decay over an interval much shorter than the evolutionary time from the main-sequence to the red-giant region. Mass transfer and subsequent decay would therefore leave the stellar photosphere enhanced in s-process elements but without Tc. In what has become almost a paradigm, then, the Tc deficiency serves as a marker for binary PRG stars which are "accidental" or "spectroscopic" or "extrinsic" rather than real or "evolutionary" or "intrinsic". It is precisely upon these masqueraders that we now focus our attention.

1 Periodic radial velocity variations

An obvious and unequivocal test for binarity is the presence of periodic radial velocity variations. Because S stars are somewhat faint, however, considerable time on a large telescope is necessary to obtain the requisite repeated, high-resolution spectra. Until recently, only scattered results were available. An orbit had been determined for only one S star, the (no-Tc) S star HR 1105 (Griffin 1984). A systematic search for periodic radial velocity variations included a few S stars (Beavers and Eitter 1986). A preliminary report on a long-range program for studying 10 non-mira S stars with CORAVEL showed significant radial velocity variations for several (Jorissen and Mayor 1988).

It was also noted that there is a larger dispersion in radial velocities for known masqueraders (no-Tc) than other S stars (Brown et al. 1990), and this strongly points to binarity. The (no-Tc) S star HR 363 has also been recently shown to be a radial-velocity variable with P> 2000 day (Eitter 1991: private communication).

In a continuation of their earlier work, Jorissen and Mayor (1991; see also Jorissen, this meeting) have now continuously surveyed 10 non-mira S stars over a period of several years. Of the 10 stars, 7 are definitely spectroscopic binaries. Orbital elements are obtained for 5 stars, whereas 2 others are long-period binaries, with P > 2000 days. The authors therefore state that 70% of S stars are binary. If accepted at face value, this statistic would make most S stars accidental (no-Tc), and would require a considerable rethinking of our ideas of AGB evolution. However, this statistic is based on only 10 stars (the Tc contents of which are unknown, by the way, except for 3 stars). Furthermore, these stars were chosen to be non-variable (to avoid ambiguity between radial velocity and pulsational velocity), and such a choice selects in favor of accidental (no-Tc) stars, which are generally the warmer, lower-luminosity, and less-variable members of the set of S stars. The mass function for S stars indicates that the companions are likely white dwarfs (Jorissen and Mayor 1991), as is the case for Ba stars (McClure and Woodsworth 1991). Binary systems with periods shorter than 600 days may be lacking among S stars although they are present among Ba stars, but this might be due to the vagaries of their small sample. Moreover, these authors find the S stars to be less massive on the average than Ba stars (Jorissen and Mayor 1991). Such a mass difference, if confirmed, would present a substantial obstacle for the suggestion, implicit here, that (no-Tc) S stars are simply evolved Ba stars (cf. Smith and Lambert 1988).

At a price of several years of work on major telescopes, radial velocity variations hold the potential to reveal fundamental data on binary S stars, and we encourage this effort.

2 Direct detection of the WD in the ultraviolet

An equally direct test for binarity is to detect ultraviolet light from the WD companion with IUE, and such a search has been carried out over several years. Preliminary detections of WD companions to HR 363 and HR 1105 (Ake, Johnson, and Peery 1988), the discovery of a hot companion to the S star 4 o^1 Ori (Ake and Johnson 1988), the discovery of the strongly interacting S-star system ER Del (Johnson and Ake 1989), and the investigation of the companion to the S star HD 35155 (Ake, Johnson, and Ameen 1991) have already been published, as have searches for hot companions of several S stars by other investigators (Peery 1985; Smith and Lambert 1988).

Examples of IUE SWP spectra of three stars (HR 363, HD 191226, and o^1 Ori) along with that of a similar M giant (μ UMa) are shown in Figure 1. Compared to the M giant, slight excess light is seen in HR 363, but the excess can only be demonstrated beyond doubt by a comparison of ultraviolet and visual flux with those of similar single stars (Ake, Johnson, and Peery 1988). Excess flux from the white-dwarf companion to HD 191226 is quite likely present (a streak on the photowrites confirms this extra light), and ultraviolet light from a WD in o^1 Ori is obvious. Useful comparisons can also be made with IUE observations of certain Tc-rich S stars (Smith and Lambert 1988). In these, as in μ UMa, no hint of excess ultraviolet emission was seen.

We have assembled and discussed in a preliminary way all IUE SWP observations of S stars (Johnson et al. 1991). From these we have constructed the following "truth table" for the correlation of Tc and binarity (Johnson, Ake, and Ameen 1991). From the table it is seen that 5 of 5 (no-Tc) S stars have WD companions, while only 1 of 8 real (yes-Tc) S stars has a companion (o^1 Ori). The hypothesis that (no-Tc) S stars are mass-transfer binaries is strongly supported. It must be understood that a failure to detect a WD companion only sets an upper limit on its luminosity. Very old WD's could still be present. To find these in a task for HST.

Table 1: Correlation of WD Companions and Tc

	Tc absent	Tc present
No WD Companion		HR 85 HR 3639 HR 4647 ST Her OP Her HR 8062 HR 8714
WD Companion	HR 363 HR 1105 HD 35155 V613 Mon HD 191226	o^1 Ori

3 Line emission in the visual

Symbiotic stars are interacting binaries consisting of a red giant and a companion which might be either a main-sequence star or a WD (cf. Kenyon 1984). Emission in the Balmer lines is one of the distinguishing characteristics of such objects, whose spectra often show lines of He I, He II, C IV, and O VI. One wonders whether the (no-Tc) S stars might also show emission, especially since IUE spectra reveal several of these to be interactive binaries, with C IV and Si IV lines in emission.

A systematic search of the literature fails to turn up any notice of unusual emission. However, Balmer alpha is definitely in emission in ER Del on two spectra taken by Ake, and it has been suggested that ER Del is an incipient symbiotic star (Johnson and Ake 1989). Searches stimulated by our IUE observations have shown Balmer-alpha emission in HD 35155 (Smith 1988: private communication); more recently, emission is seen in both HD 35155 and in HR 1105 (Bopp 1991: private communication). Thus it appears that at least the strongly interactive S binaries are related to symbiotic stars.

In 1979, a claim was made, based on a spectrum of medium resolution, that the star HR 1105 showed a very strong line of He I λ10830 (Shcherbakov 1979). In spectra of normal M giants the 10830 line is absent or very weak (Zirin 1976, 1982; O'Brien and Lambert 1986, Lambert 1987), and this is understood on the basis of the high excitation energy ($\sim$ 20 ev) of the lower level (2^3S) of the line and the relatively low-temperature chromospheres of M giants. The great strength of 10830 in HR 1105 was confirmed by a high-resolution observation taken at Kitt Peak (Brown, Johnson, and Hinkle 1989), which showed a line of 2.2 A equivalent width.

Additional spectra of He I λ10830 in a number of non-mira S stars, both with and without Tc, were taken at Kitt Peak and at McDonald Observatory. The results were dramatic. Of 7 (no-Tc) S stars, all 7 show easily detectable He I features (in absorption, emission, or both); only 1 out of 13 (yes-Tc) S stars shows a detectable He I feature. The presence of 10830 in spectra of the (no-Tc) S stars signals the presence of source of energy besides the red-giant chromosphere – either the WD companion itself, an accretion disk, or a gas stream, and this agrees with the presence, in spectra of several of these systems, of ultraviolet emission lines of high excitation. In addition, (no-Tc) S stars display substantially larger variations in radial velocity (over a year of observation), presumably linked to the presence of a white-dwarf companion. Thus the relation between binarity and 10830 emission is strong, and the 10830 line effectively serves as an indirect indicator of both Tc-deficiency and binarity (Brown et al. 1990).

4 Infrared emission

Most red giants of spectral type later than about M5 show excess infrared emission indicative of circumstellar dust, and this dust is assumed to indicate mass loss. In a parallel fashion radio observations of circumstellar gas show an outflow commonly called a red-giant wind. Mass-loss rates of 10^{-8}-10^{-4} $M_{\odot}$/yr are obtained, with an increase to higher values toward the end of the star's AGB lifetime. Mass loss from S stars is discussed by Jura (1988).

Although there is no direct theoretical reason to connect the two, the mass loss appears to increase at approximately the same evolutionary point on the AGB as dredge up begins. Thus one might expect the normal (evolutionary or yes-Tc) S stars to show large infrared excesses and correspondingly redder colors while the "accidental" (no-Tc) stars would display smaller or no infrared excesses.

In fact, quantitative correlations of stellar properties with various infrared colors has been a popular game (cf. Van der Veen and Habing 1988; Walker and Cohen 1988). As a result, colors of red giants without any circumstellar material have been carefully determined. For example, it has been estimated (Jura 1986) that a typical red-giant photosphere has a ratio of energy fluxes at 12 and 2.2 μm of R_1 = f(12μm)/f(2.2μm) = 0.10 and any value larger than this must indicate CS emission. The corresponding figure for the ratio of fluxes at 25 and 12μm is R_2 = f(25μm) f(12 μm) = 0.33 (van der Veen and Habing 1988).

With a list of 30 stars for which both information on the presence or absence of Tc and the infrared fluxes at 2.2 and 12 μm are available from the literature, the above idea has been tested (Frayer and Johnson 1991). For this sample, 7 (no-Tc) S stars have values of R_1 between 0.063 and 0.083, while 23 (yes-Tc) S stars have values between 0.078 and 0.244. That is, all the (no-Tc) S stars fall below a value of R_1 = 0.09, while normal (yes-Tc) S stars have a large range of values. In particular, only 4 of 23 normal (yes-Tc) S stars have values below 0.084. The (yes-Tc) S stars with these low values of R are presumably those which have just begun (third) dredge up but have not yet begun to shed significant quantities of mass. In fact, this finding suggests that dredge up precedes the initiation of the red giant wind.

A test with R_2 yields parallel results. All (no-Tc) S stars are confined below $R_2 = 0.30$, while (yes-Tc) S stars have values over the entire range from 0.25 to 0.53. More specifically, 7 (no-Tc) S stars have ratios of $R_2 = F(25\ \mu m)/F(12\ \mu m)$ between 0.24 and 0.30, while 23 (yes-Tc) S stars have values ranging from 0.25 to 0.53, and only 7 of 23 have values of R_2 below 0.30 (Frayer and Johnson 1991).

If low values of infrared colors serve as surrogates for the absence of Tc and the presence of binarity in S stars, we can examine the larger question of the binarity of S stars from the longer list of infrared-bright S stars (Wing and Yorka 1979). Of 64 S stars, only 8 (12%) have values of R_1 less than 0.09 (Frayer and Johnson 1991). These, or at least some of these, are apparently the accidental S stars. This low fraction contrasts strongly with the higher fractions of accidental (no-Tc) S stars (38%-70%) found in earlier surveys (LLB; SL88; Jorissen and Mayor 1991). However, there are likely selection effects in the earlier lists, and the lower value found from Wing and Yorka is probably more representative.

5 Discussion and Conclusions

Although most S and MS stars seem to fit well into the M-S-C sequence and their enrichment of s-process elements and carbon appears to be satisfactorily explained by the third dredge up in low-mass stars (1-3 M$\odot$), certain stars (30-40% of bright S stars) stand out by their lack of the unstable element Tc, which is otherwise observed in most late AGB stars. By analogy with Ba stars and CH stars, which are also enriched in s-process elements and carbon but not Tc, and whose unusual abundances are quite clearly due to earlier mass transfer from a companion (now a WD), a popular hypothesis states that all Tc-deficient S and MS stars are mass-transfer binaries rather than AGB stars. Here we have reviewed the evidence from radial velocities, ultraviolet detection of the WD, visual emission lines (especially H I and He I), and infrared colors.

We conclude the following.

1. Like the Ba stars and CH stars, the Tc-deficient S stars tend to show radial velocity variations, and several of these are periodic with periods of the order of 2 years.

2. Several white-dwarf companions have been discovered for (no-Tc) S stars with IUE; ordinary (yes-Tc) S stars tend not to have companions. The WD's discovered so far are so old (their cooling times are so long) that mass transfer must have occurred early in the life of the present red giant, probably while it was still on the main sequence.

3. Strong lines of He I 10830 A are found in all Tc-deficient S stars searched and are not found in ordinary S stars. This finding strongly hints of interaction and further strengthens the link between the Tc-deficiency and binarity.

4. Infrared observations show that Tc-deficient S stars have low IR colors while ordinary S stars show a large range, including some very large values. This strengthens the view that Tc-deficient S stars are not AGB stars and are likely mass-transfer objects.

5. A fairly high fraction of the known binary systems are found to be interacting. This finding appears to connect these stars both with the interactive Ba stars and

perhaps with the symbiotic stars and suggests new research on the Tc-deficient S and MS stars.

Although all evidence supports the hypothesis that (no-Tc) S stars are formed by mass transfer from a binary companion, the issue cannot be settled definitely until answers can be provided to several further questions. What kind of AGB stars were the mass donors in each case? What are the detailed dynamics of mass transfer? Can we find main-sequence S stars that will evolve to (no-Tc) S stars? We look forward to the vigorous investigations these questions deserve.

Sincere thanks are due to Tom Ake, with whom the author has collaborated for several years in a search with IUE for the WD companions to S stars. We acknowledge financial support from the organizers of this conference and from NASA.

6 References

Ake, T.B. and Johnson, H.R. 1988, Astrophys. J. 327, 214.

Ake, T.B., Johnson, H.R., and Perry, B.F. 1988, in A Decade of UV Astronomy with IUE, ESA SP-281, p. 245.

Ake, T.B., Johnson, H.R., and Ameen, M.M. 1991, Astrophys. J., in press.

Beavers, W.I. and Eitter, J.J. 1986, Astrophys. J. Suppl. 62, 147.

Bessell, M.S., Wood, P.R., and Lloyd Evans, T. 1983, Mon. Not. R.A.S. 202, 59.

Brown, J.A., Johnson, H.R., and Hinkle, K.H., 1989, in Evolution of Peculiar Red Giant Stars, ed. H.R. Johnson and B. Zuckerman (Cambridge: Cambridge Univ. Press), p. 378.

Brown, J.A., Smith, V.V., Lambert, D.L., Dutchover, E., Hinkle, K.H., and Johnson, H.R. 1990, Astron. J. 99, 1930.

Frayer, D.T. and Johnson, H.R. 1991, in preparation.

Griffin, R.F. 1984, *Observatory* 104, 224.

Iben, I. 1987, in Late Stages of Stellar Evolution, ed. S Kwok and S.R. Pottasch (Dordrecht: Reidel), p.175.

Iben, I. and Renzini, A. 1983, Ann. Rev. Astr. Ap. 21, 277.

Johnson, H.R. and Ake, T.B. 1989, in Evolution of Peculiar Red Giant Stars, ed. H.R. Johnson and B. Zuckerman (Cambridge: Cambridge Univ Press), p.371.

Johnson, H.R., Ake, T.B., Ameen, M.M., and Brown, J.A. 1989, in From Miras to Planetary Nebulae, ed. M.O. Mennessier and A. Omont (Gif sur Yvette: Ed. Frontiers), p. 332.

Johnson, H.R., Ake, T.B., and Ameen, M.M. 1991, Astrophys. J. in preparation.

Jorissen, A. and Mayor, M. 1988, Astron. Astrophys. 198, 187.

Jorissen, A. and Mayor, M. 1991, Astr. Ap., in preparation.

Jura, M. 1986, Publ. Irish Astron. Soc. 17, 322

Jura, M. 1988, Astrophys. J. Suppl., 66, 33.

Kenyon, S.J. 1986, The Symbiotic Stars (Cambridge: Cambridge Univ. Press), p. 115.

Lambert, D.L. 1987, Astrophys. J. Suppl. 65, 255.

Lambert, D.L. 1991, in The Photospheric Abundance Connection, ed. G. Michael and

A. Tutukov (Dordrecht: Kluwer), p. 299.
Lattanzio, J.C. 1989, in Evolution of Peculiar Red Giant Stars, ed. H.R. Johnson and B. Zuckerman (Cambridge: Cambridge Univ. Press), p.161.
Little, S.J., Little-Marinen, I.R., and Bauer, W.H. 1987, Astron.J. 94, 987 (LLB).
Little-Marenin, I.R. 1989, in Evolution of Peculiar Red Giant Stars, ed. H.R. Johnson and B. Zuckerman (Cambridge: Cambridge Univ. Press) p. 131.
Little-Marenin, I.R. and Little, S.J. 1979, Astron. J. 84, 1374.
Lloyd Evans, T. 1984, Mon. Not. R.A.S. 208, 447.
McClure, R.D., Fletcher, J.M., and Nemec, J.M. 1980, Astrophys. J. Lett. 238, L35.
McClure, R.D. and Woodsworth, A.W. 1991, Astrophys. J. 280, L31.
Merrill, P. 1952, Astrophys. J. 116, 21.
Peery, B.F. 1985, in Cool Stars with Excesses of Heavy Elements, ed. M. Jaschek and P.C. Keenan (Dordrecht: Reidel), p. 333.
Peery, B.F. 1986, in New Insights in Astrophysics: 8 Years of UV Observations with IUE, ed. E.J. Rolfe, ESA SP-263, p.117.
Scalo, J.M. and Miller, G.E. 1981, Astrophys. J. 246, 251
Shcherbakov, A.G. 1979, Sov. Astron. Lett. 5, 290.
Smith, V.V. and Lambert, D.L. 1985, Astrophys. J. 294, 326.
——————— 1986, Astrophys. J. 311, 843.
——————— 1987, Astron. J. 94, 977.
——————— 1988, Astrophys. J. 333, 219.
——————— 1990, Astrophys. J. Suppl. 72, 387.
van der Veen, W.E.C.J., and Habing, H. 1988, Astron. Astrophys. 194, 125.
Walker, H.J. and Cohen, M. 1988, Astron. J. 95, 1801.
Wing, R.F. and Yorka, S.B. 1977, Mon. Not. R.A.S. 178, 383.
Wood, P.R. 1985, in Cool Stars with Excesses of Heavy Elements, ed. M. Jaschek and P.C. Keenan (Dordrecht: Reidel), p. 357.
Zirin, H. 1986, Astrophys. J. 208, 414.
Zirin, H. 1982, Astrophys. J. 260, 655.

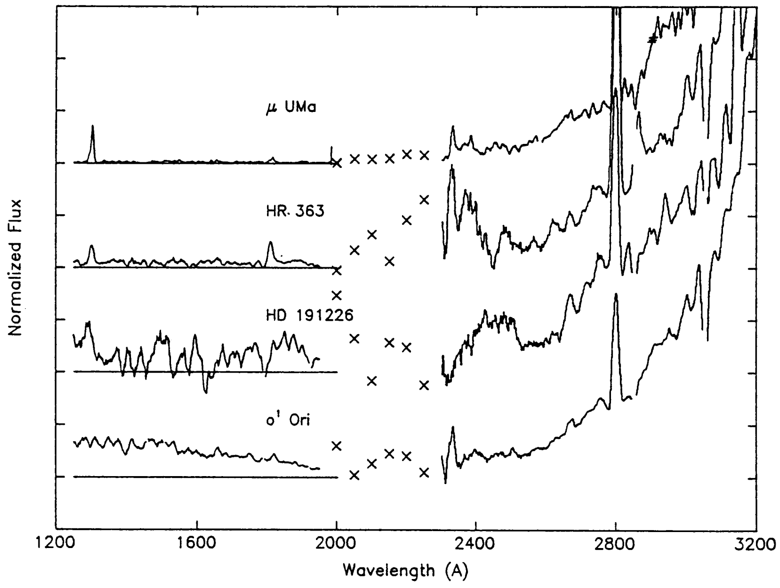

Figure 1. IUE SWP spectra of (top to bottom) the M giant star μ UMa (M0 III), the (no-Tc) S stars HR 363 and HD 191226, and the (yes-Tc) S star o[1] Ori. Excess ultraviolet light indicative of a WD companion may be present in HR 363, is likely present in HD 191226, and is definitely present in o[1] Ori.

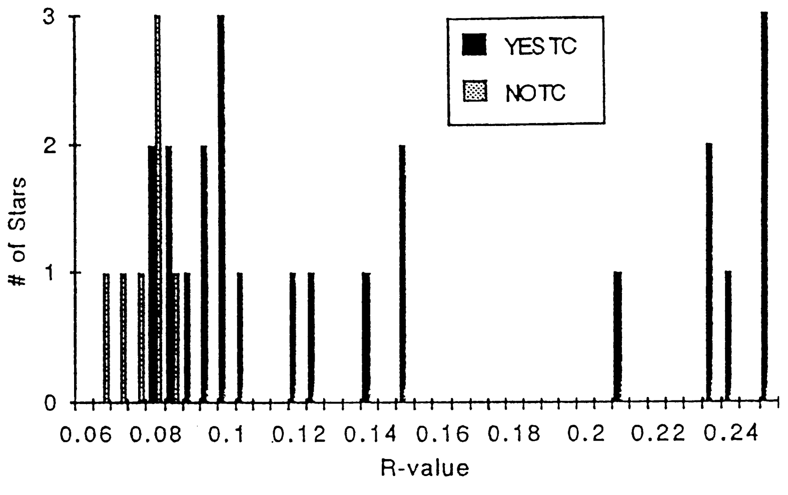

Figure 2. Values of the distribution of $R \equiv R_1 = f(12\ \mu m)/f(2.2\mu m)$ for 30 S stars for which values of $f(2.2\mu m)$, $f(12\ \mu m)$, and information or the presence or absence of Tc are known. As is clear, the (no-Tc) S stars are strongly confined to low (essentially photopheric) values of the ratio, while normal (yes-Tc) S stars scatter over a wide range. (See text.)

https://doi.org/10.1017/S0074180900122156 Published online by Cambridge University Press