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On the infrared properties of S-stars with and without technetium

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Abstract. There exist S-stars with and without technetium in their spectra. The S-stars with technetium are considered to be thermal pulsing AGB stars, while the S-stars without technetium are usually thought to be giants which acquired their s-process material from a (presently unseen white dwarf) companion. I investigate the possibility of discriminating between S-stars with ("intrinsic" S-stars) and without ("extrinsic" S-stars) technetium solely on the basis of their infrared properties. I find that intrinsic S-stars have a circumstellar envelope, while the infrared properties of extrinsic S-stars are consistent with (warm) stellar blackbodies with no or very little circumstellar material. This is reflected in the IRAS PSC fluxes, the LRS spectra and $V-[12]$ colour of the intrinsic and extrinsic S-stars. I find that S-stars with $S_{25}>0.30S_{12}$ are intrinsic S-stars, stars with $0.25S_{12}<S_{25}<0.30S_{12}$ can both be intrinsic or extrinsic S-stars and stars with $S_{25}<0.25S_{12}$ are extrinsic S-stars. The LRS spectra of the extrinsic S-stars closely follow a $F_\nu \sim \lambda^{-2}$ law, indicative of a (warm) stellar blackbody. The LRS spectra of the intrinsic S-stars either show emission features near 10 and 19 μm or are featureless and characterised by cool blackbody temperatures. I find that 96% of S-stars with $V-[12]>7.0$ are intrinsic and all S-stars with $V-[12]\leq 5.0$ are extrinsic. S-stars with intermediate $V-[12]$ colour can belong to both groups. The infrared properties of the intrinsic and extrinsic S-stars are consistent with the evolutionary phase envisioned for both groups. I estimate that between 50% and 70% of S-stars in an optically complete sample are extrinsic S-stars.

Key words: circumstellar matter – stars-evolution – stars-late type

1. Introduction

Traditionally S-stars are thought to be an intermediate phase of AGB evolution between M-stars and C-stars. The S-stars are characterised by nearly equal carbon and oxygen abundance in the photosphere and enhancement of the s-process elements relative to iron. Spectroscopically they are classified by means of the ZrO and LaO bands in the visual part of the spectrum. In recent years it has become clear that this picture has to be revised.

The unstable isotope ^{99}Tc, which is produced in the s-process during third dredge-up on the AGB, has a half life of $\tau_{1/2}=2\,10^5$ yr for $T\lesssim 10^8$ K, decreasing to $\tau_{1/2}=1$ yr at $T=3.5\,10^8$ K (Schatz 1983). Detailed studies of the s-process indicate that the more rapid decay of Tc at higher temperatures is offset by an enhanced production rate due to a higher neutron flux (Mathews et al. 1986) leaving the Tc abundance almost unaltered. In the power down phase after a thermal pulse Tc is therefore mixed into the envelope. Because the interpulse period between two consecutive thermal pulses of $\lesssim 10^5$ yr (for core masses of $\gtrsim 0.58 M_\odot$, Boothroyd & Sackmann 1988) is shorter than the Tc half life, it is expected that Tc shows up in all thermal pulsing AGB stars.

It was therefore surprising that ~40% of stars of spectral type MS and S (I will refer to both classes simply as S-stars) do not show Tc in their spectra (Little et al. 1987; Smith & Lambert 1988). Iben & Renzini (1983) put forward the idea that the S-stars without Tc are evolved Barium stars, which are G and K giants without Tc but with enhanced s-process elements. The discovery that the Barium stars are spectroscopic binaries (McClure et al. 1980; McClure 1983; Jorissen & Mayor 1988; McClure & Woodsworth 1990) has led to the scenario that Barium stars are the result of mass transfer from an AGB star [now a white dwarf (WD)] to a less evolved companion (now the Barium star). If the S-stars without Tc are evolved Barium stars they too must be spectroscopic binaries. The extrinsic S-stars which have been observed for binarity are indeed member of WD containing binary systems (Jorissen & Mayor 1988, 1992; Brown et al. 1990). Although the reverse is difficult to prove, radial velocity measurements, observations of the He I line at 1.0830 μm (Brown et al. 1990) and IUE data (Smith & Lambert 1987; Johnson et al. 1992) are consistent with the proposition that intrinsic S-stars are not members of a WD containing binary system.

Of the about 1300 S-stars known in the Galaxy only 60 or so have been observed for the presence of Tc. Since the fraction of extrinsic S-stars is substantial it would be important to be able to separate extrinsic and intrinsic

S-stars by means of another (indirect) criterium. Since the extrinsic S-stars are supposed to be less luminous, hot and probably have low mass loss rates while the intrinsic S-stars are luminous, cool AGB stars, surrounded by a circumstellar shell, the infrared characteristics of both classes of S-stars may be very different.

In this paper I investigate the infrared properties of the intrinsic and extrinsic S-stars. I define the sample in Sect. 2. The IRAS colour–colour diagram and the $V-[12]$ colour are discussed in Sect. 3. The LRS spectra are discussed in Sect. 4. I conclude in Sect. 5.

2. The sample

All stars classified as MS or S and observed for the presence of Tc were selected from Little et al. (1987) and Smith & Lambert (1988, 1990; hereafter SL88 and SL90). The 39 stars with Tc and the 30 stars without Tc were cross correlated with the S-star catalog of Stephenson (1984) and it turned out that 12 stars were not listed there. For those 12 stars the spectral types listed in the literature were more closely examined. Stars with Tc that subsequently were excluded are: HR 4647 [classified as M4 III by Hoffleit (1982), as M4/5 by Houck (1988) and as M4S by SL88. The star shows no enhanced s-process elements (SL90)], R Hya [classified as M7 IIIe by Hoffleit (1982), as M6.5e by Keenan et al. (1974), as M6/7 by Houck (1988) and as M6e-M9eS by the general catalog of variable stars (GCVS, Kholopov et al. 1985)] and Z Sgr [classified as M5e by Keenan et al. (1974) and as M4e-M9(Se) in the GCVS]. Stars without Tc that were excluded are: HR 2508 [classified as M1 Ib-IIa by Hoffleit (1982) and as M2 IIabS by Bidelman (1980). This star shows no enhanced s-process elements (Smith & Lambert 1986)], RT Aql [Keenan et al. (1974) observe no ZrO and classify it as M 7. The star is listed as M6e-M8e(S) in the GCVS] and X Cet [classified as M3e by Keenan et al. (1974) and as M2e(S) -M6e in the GCVS].

The final sample consists of 27 stars without Tc and 36 stars with Tc. They are listed in Tables 1 (intrinsic S-stars) and 2 (extrinsic S-stars) where the number in Stephenson's catalog, the HR/HD/BD number, the variable star name and the spectral type (from Stephenson 1984, Hoffleit 1982 or the GCVS) are given.

There are two stars in the sample which deserve some further attention. They are o^1 Ori and DY Gem. Omicron Ori has Tc in its spectrum (Little et al. 1987; SL88; Vanture et al. 1991) but has a WD companion (Ake & Johnson 1988). Ake and Johnson conclude that the cooling time of the WD is far in excess of the Tc half life so that o^1 Ori may be an evolved Barium star which has reached the TP-AGB (Brown et al. 1990) or is a case of parallel evolution of two stars, one of which is now a WD and the other an AGB-star (Ake & Johnson).

DY Gem has no Tc in its spectrum (SL90) but has all characteristics of a true TP-AGB star. From SL90 I derive that 89% (8/9) of the intrinsic S-stars have C/O$\geq$0.49, while 67% (10/15) of the extrinsic S-stars have C/O$\leq$0.47. The C/O ratio of 0.88 and the $^{12}C/^{13}C$ ratio of 30 ± 7 (SL90) in DY Gem are probably the result of nucleosynthesis in DY Gem and not from material accreted from a companion. I was informed by V. Smith (private communication) not to put too much weight on the "non detection" of Tc in DY Gem since the spectrum was complicated and difficult to measure.

Other stars in our sample which have known WD companions are the extrinsic S-stars HR 363, HR 1105, HD 35155, V613 Mon and HD 191226 (Hoffleit 1982; Griffin 1984; Jorissen & Mayor 1992; Johnson et al. 1992). In the intrinsic S-stars HD 1760, RS Cnc, ST Her, HR 6702, HR 8062 and HR 8714 no WD companion has been detected (Smith & Lambert 1987; Johnson et al. 1992). Three stars in the sample have main sequence companions: HR 8815, HD 191589 and π^1 Gru.

The 63 stars were correlated on position with the point source catalog (PSC, JISWG 1986). All stars were detected by IRAS except HD 199799 and HR 8062 which are in a part of the sky not surveyed by IRAS. In Tables 1 and 2 the not-colour-corrected fluxes at 12, 25 and 60 μm flux are listed. From the LRS atlas (JISWG 1986) and the additional work of Volk & Cohen (1989) and Volk et al. (1991) the LRS classification is listed.

3. The IRAS colour-colour diagram

In Fig. 1. the $C_{21} = 2.5 \log(S_{25}/S_{12})$ versus $C_{32}=2.5 \log(S_{60}/S_{25})$ color–color diagram for the extrinsic (O) and

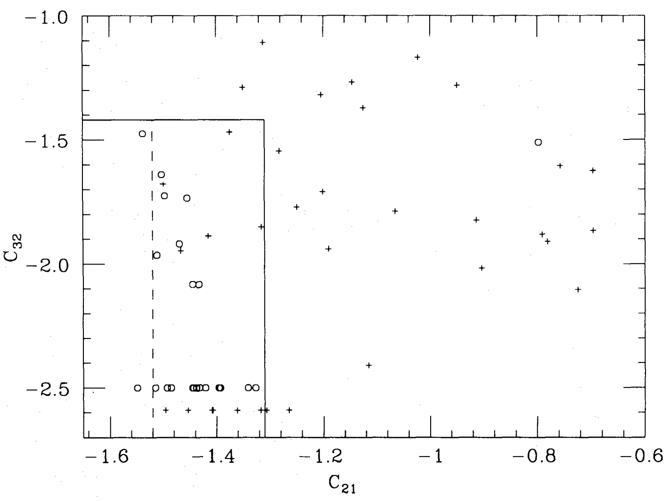

Fig. 1. The IRAS colour-colour diagram. Plotted are the S-stars with Tc (+) and without Tc (O). The stars without 60 μm flux are plotted at $C_{32}=-2.59$ and -2.50 respectively. The intrinsic S-stars are located at $C_{21}>-1.31$ and $C_{32}>-1.42$. Stars with $-1.52<C_{21}<-1.31$ and $C_{32}<-1.42$ can belong to both groups. Stars with $C_{21}<-1.52$ are extrinsic. These areas are indicated. The star located at $C_{21}\approx-0.8$, $C_{32}\approx-1.5$ is DY Gem

Table 1. The S-stars with Tc

S	HD/HR/BD	name	sp. type	S_{12} (Jy)	S_{25} (Jy)	S_{60} (Jy)[a]	LRS[b]
8	HD 1760	T Cet	M5-6S	198	55.8	14.4	16
9	HD 1967	R And	S5-7	327	168	24.2	*E*
12	HD 4350	U Cas	S5/3	8.38	2.49		01
49	HD 14028	W And	S7/1	167	72.1	13.5	22
89	BD 23 654		S	24.4	7.30	2.63	*S*
103	HD 29147	T Cam	S6/5	41.3	11.9	3.63	17
114	HR 1556	o[1] Ori	M3S	85.4	21.4	4.57	18
116	BD 48 1187	TV Aur	S5/6	12.9	4.25	1.26	
149	HD 37536	NO Aur	M2S	43.5	22.9	5.12	43
307	HD 53791	R Gem	S5/5	21.6	7.52	2.34	16
312	HD 54587	AA Cam	M5S	14.5	6.06	1.86	
347	HD 58521	Y Lyn	M6S	122	64.2	11.5	23
403	HD 63334	T Gem	S4/4	3.73	1.02		
		V Gem	M4.5S	9.24	3.31	0.36:	
411	HD 63733		S4/3	2.20	0.66		
422	HD 64332	NQ Pup	S5/2	7.02	1.84		
589	HR 3639	RS Cnc	M6S	480	209	32.6	22
803	HD 110813	S UMa	S3/6	4.23	1.40	0.29:	
866	HD 131169	S Lup	Se	7.78	2.22		
903	HD 142143	ST Her	M6.5S	199	97.1	16.7	41
	BD 15 3063	S Her	M5S	34.3	11.5	1.92	17
	HR 6702	OP Her	M5 IIbS	54.1	17.1	3.35	17
1053	HD 170970		S3/1	5.08	1.39		
1070	HD 172804	V679 Oph	S5/6	4.43	1.21		
1099	HD 177175	V915 Aql	S5/2	11.0	3.36	0.81:	
1117	HD 180196	T Sgr	S5/6	40.3	14.3	4.04	*F*
1150	HD 185456	R Cyg	S6/6	105	52.2	12.0	22
1165	HR 7564	χ Cyg	S7/1.5	1690	459	80.7	*E*
1188	HD 190629	AA Cyg	S6/3	40.0	15.5	5.27	31
1226	HD 195763	Z Del	S4/2	3.11	0.97		
1254	HD 199799		MS	[c]			
	HR 8062		S4/1	[c]			
1292	HD 211610	X Aqr	S6,3	11.5	4.31	0.83:	
1294	HR 8521	π^1 Gru	S5,7	909	437	77.3	42
1315	HR 8714	HR Peg	S4/1	27.6	7.15	1.19	*S*
1346	HD 224960	W Cet	S5-7/1.5-3	13.3	3.96	0.72	16

[a] A (:) means a flux of moderate quality, no entry means only an upperlimit is listed in the PSC.
[b] The letters *F*, *S*, *E* are used in the classification scheme of Volk & Cohen (1989) and Volk et al. (1991). The counterparts in the usual LRS classification are: F=10–16, S=17–19, E=2n.
[c] In a region of the sky not observed by IRAS.

intrinsic S-stars (+) is plotted. The stars without 60 μm flux are plotted at constant $C_{32}=-2.50$ and -2.59 respectively. There is a clear correlation: all S-stars with $S_{25}>0.30\ S_{12}$ ($C_{21}>-1.31$) are intrinsic S-stars. The region $C_{21}<-1.31$ is populated by both intrinsic and extrinsic S-stars. Furthermore there are no extrinsic S-stars with $S_{60}>0.27\ S_{25}$ and the two stars with $C_{21}<-1.52$ are extrinsic. This conclusion is consistent with the idea that the mass loss in extrinsic S-stars is low: blackbodies with 2000 K $<T_{\rm eff}<10\,000$ K are located at $-1.41<C_{21}<-1.56$ and $-1.88<C_{32}-1.88$. The only exception to our conclusion is DY Gem which was discussed in Sect. 2.

If the intrinsic and extrinsic S-stars have very different infrared properties this should also be reflected in the $V-[12]$ colour. In Fig. 2 a histogram of the $V-[12]$ colour for the intrinsic and extrinsic S-stars is presented. The V magnitudes are taken from Stephenson (1984) or, if not listed there, from Hoffleit (1982) or the GCVS [1]. There is a clear correlation: S-stars with $V-[12]>7$ are intrinsic and S-stars with $V-[12]\leq 5$ are extrinsic. S-stars with intermediate colours can belong to both groups. The exceptions are DY Gem and V Cnc both with $V-[12]$

[1] For stars in the GCVS the mean visual magnitude is taken, consistent with the entries in Stephenson's catalog.

Table 2. The S-stars without Tc

S	HD/HR/BD	name	sp. type	S_{12} (Jy)	S_{25} (Jy)	S_{60} (Jy)[a]	LRS
22	HD 6409		M2wkS	5.64	1.50		
26	HR 363		S3/2	11.5	3.01	0.61:	
79	HR 1105	BD Cam	S4/2	41.0	10.8	1.59	18
133	HD 35155		S4,1	7.98	2.01	0.41	16
231	BD 14 1350	DY Gem	S8,5	21.7	10.4	2.59	42
260	HD 49368	V613 Mon	S3/2	4.31	1.09		
382	HR 2967	NZ Gem	M3S	25.2	6.50	1.11	18
494	HD 70276	V Cnc	S3/6e	8.41	2.02		
566	BD 06 263		M3S	0.97			
	HR 4088	DE Leo	M3 IIIabS	14.29	3.58	0.79	01
712	BD−10 3156		M3S	0.88			
722	HD 96360		M3[Swk]	3.18	0.84		
829	BD−2 3726		M1wkS	1.01			
926	BD 57 1671		M2S	2.38	0.62		
937	BD−13 4495		M2S	8.21	2.09		19
938	BD−18 4320		Swk	12.20	2.96	0.76	31
1023	HD 165774		S4,6	2.24	0.66		
1031	BD 16 3426		M4wkS	5.59	1.51		
	HR 7442	V1743 Peg	M4.5 IIIaS	26.0	6.95	1.02	17
1173	BD−18 5539		S2*3	1.27			
1178	HD 189581		S4*2	3.44	1.00		
1192	HD 191226		M1S M3SIIIa	4.36	1.08		
1194	HD 191589		S	2.20	0.61		
1301	BD−11 5880		M4S	3.89	1.04		
1304	BD 33 4573		Swk	1.52	0.42		
1322	HR 8815	GZ Peg	M4S	80.9	20.1	3.29	18

[a] A (:) means a flux of moderate quality, no entry means only an upperlimit is listed in the PSC.

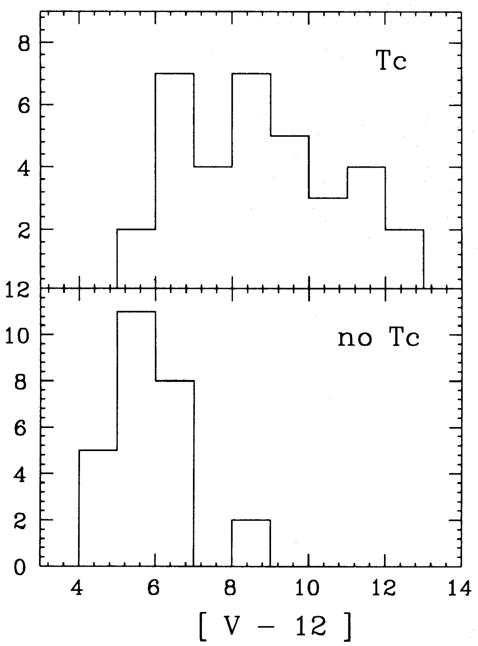

Fig. 2. The histogram of $V-[12]$ colour for the intrinsic and extrinsic S-stars. The extrinsic S-stars at $V-[12]=8.7$ are DY Gem and V Cnc

= 8.7. DY Gem is probably a TP-AGB star, as discussed in Sect. 2. V Cnc is a Mira and its V magnitude varies between 7.5 and 13.9 (GCVS). It is listed in the SAO catalog as a star of $V=7.1$. If $V=7.1$ it has $V-[12]$ = 5.8.

The lack of extrinsic S-stars with $V-[12]>7$ is not due to observational bias. Plotting the distributions of V and [12] separately shows that the distribution of V is about equal for the intrinsic and extrinsic stars (although the 5 faintest sources are intrinsic S-stars). The distribution of the 12 μm magnitudes shows that the intrinsic S-stars have in general higher 12 μm fluxes than the extrinsic S-stars.

4. The LRS spectrum

In Tables 1 and 2 the LRS classification is listed. It is well known that this classification scheme is not very reliable, requiring visual inspection of the LRS spectrum for correct classification. Furthermore, the LRS spectrum is plotted as λF_λ versus λ, while a log F_ν versus log λ plot contains additional information. Therefore the LRS spectra of the 25 stars listed in the LRS atlas were extracted. From a star without circumstellar shell it is expected that the flux

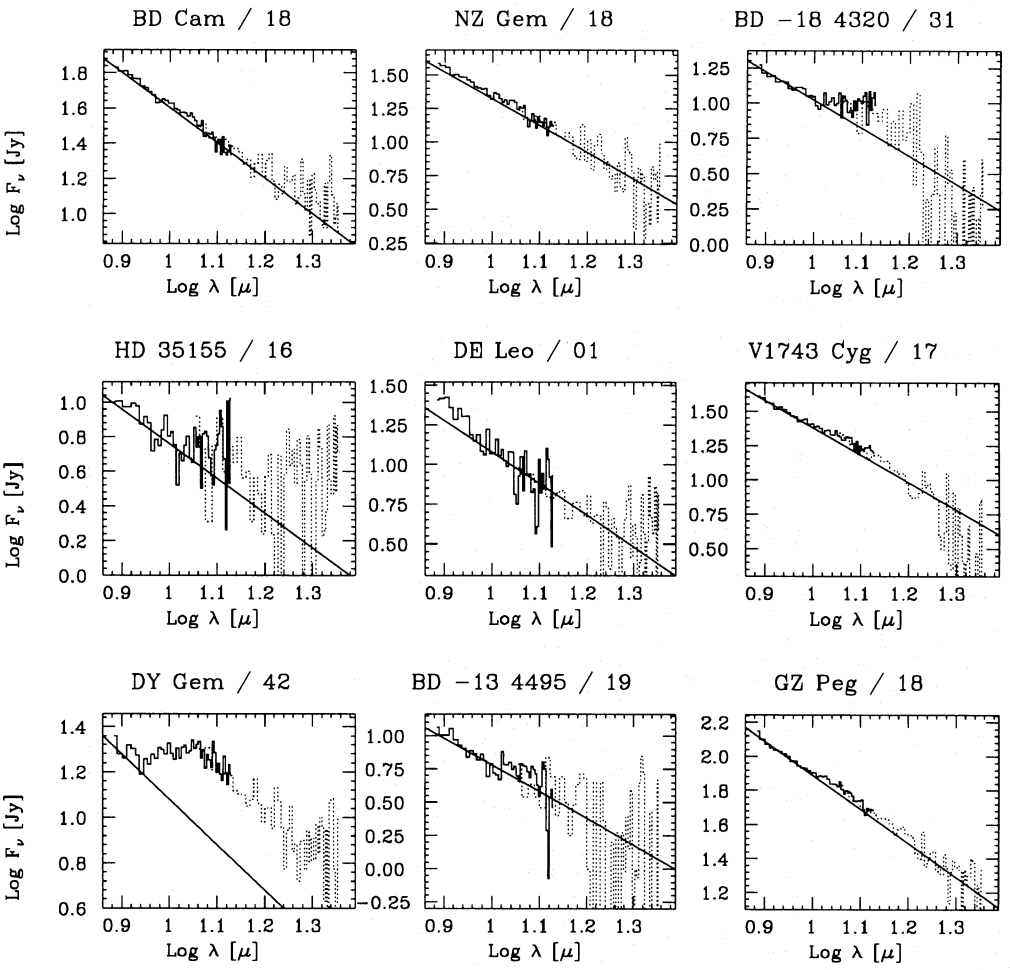

Fig. 3. The LRS spectra of the S-stars without Tc. Included is a line with slope −2. In the header the name and the LRS classification are listed. The solid and the dotted histogram indicate the blue and the red part of the LRS spectrum

comes from the photosphere which can be represented by the Rayleigh–Jeans tail ($F_\nu \sim \lambda^{-2}$) for high enough effective temperatures. In a log F_ν versus log λ plot a slope of -2 is expected for hot stars without a circumstellar shell. In Figs. 3, 4 and 5 the LRS spectra together with a line of slope -2 is plotted for the extrinsic (Fig. 3) and the intrinsic (Figs. 4 and 5) S-stars respectively. From Fig. 3 it is deduced that all intrinsic S-stars clearly follow the $F_\nu \sim \lambda^{-2}$ law in the LRS spectrum expected from hot stellar photospheres. The only exception is DY Gem, which was discussed in Sect. 2. From Figs. 4 and 5 it is clear that the intrinsic S-stars deviate significantly from a $F_\nu \sim \lambda^{-2}$ law. The only exception is o^1 Ori, which is discussed in Sect. 2. The other stars can be divided into two groups: the stars with featureless LRS spectra (U Cas, R Gem, S Her, OP Her, W Cet) and the stars which show features at $\sim$10 and $\sim$19 μm (see Little-Marenin & Little 1988 for a thorough discussion on the features observed in the LRS spectra of S-stars). The four stars classified as 4n in the LRS atlas all show (weak) 18 μm emission.

The five additional stars (all intrinsic S-stars) not in the LRS atlas but listed in Volk and Cohen (1989) and Volk et al. (1991) are not plotted. R And, T Sgr and χ Cyg clearly show emission features near 10 and 19 μm. For BD 23 654 and HR Peg it is not possible to tell if there is excess flux relative to a λ^{-2} law from the usual log $\lambda F_\lambda - \lambda$ plot.

5. Conclusions

I show that on the basis of the IRAS PSC fluxes, the $V-[12]$ colour and the LRS spectra it is possible to classify a S-star, with high probability, as an intrinsic or an extrinsic S-star. This method uses the fact that extrinsic S-stars are less luminous (these stars have supposedly not reached the tip of the AGB), have higher effective temperatures and have a low mass loss rate, while the intrinsic S-stars are luminous cool, thermal-pulsing AGB stars with a substantial mass loss rate. This makes the infrared properties of both classes very different [2].

The criteria to discriminate between extrinsic and intrinsic stars can be summarized as follows:

[2] In a recent paper Frayer & Johnson (1992) arrive at the same conclusion by considering the distribution of S(12 μm)/S(2 μm) and S(25 μm)/S(12 μm) for a smaller sample of $\sim$30 S-stars with and without technetium.

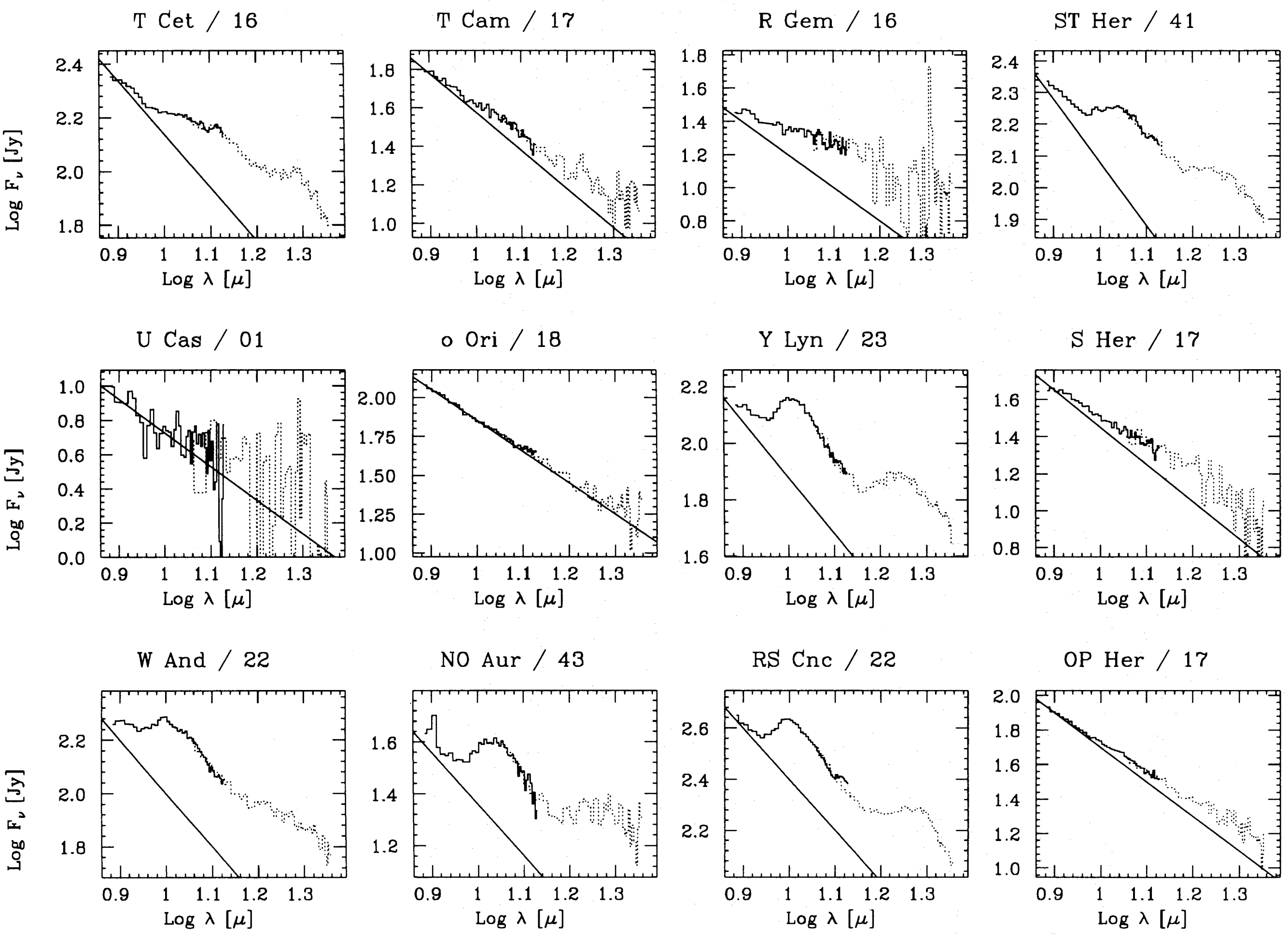

Fig. 4. The LRS spectra of the S-stars with Tc. Included is a line with slope −2. In the header the name and the LRS classification are listed.

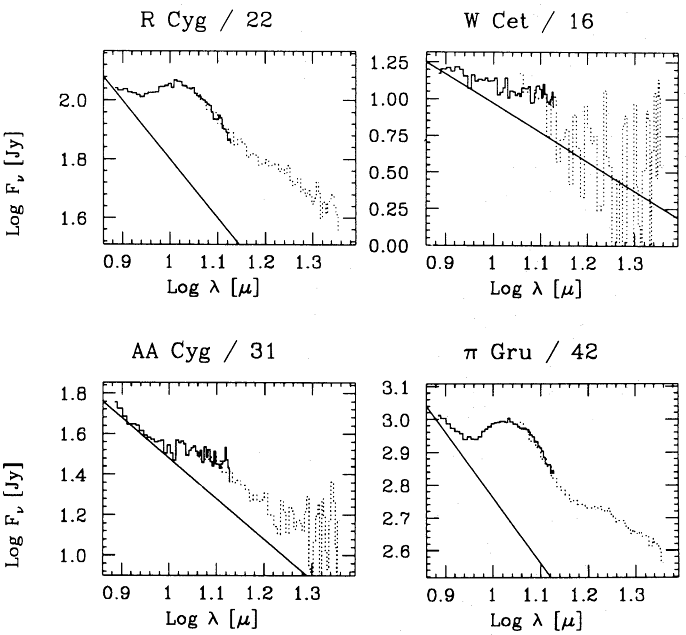

Fig. 5. As Fig. 4.

1. S-stars with $V-[12] \leq 5$ are extrinsic, stars with $5 < V-[12] \leq 7$ can be intrinsic or extrinsic and $\sim 96\%$ of the S-stars with $V-[12] > 7$ are intrinsic.

2. S-stars with $C_{21} > -1.31$ or $C_{32} > -1.42$ are intrinsic S-stars. S-stars with $-1.52 < C_{21} < -1.31$ and $C_{32} < -1.42$ can belong to both groups. Stars with $C_{21} < -1.52$ are extrinsic.

3. When the LRS spectrum is plotted as log F_ν versus log λ the extrinsic S-stars follow a line of slope –2. The intrinsic S-stars are characterised by featureless cool blackbodies or show the silicate emission features near 10 and 19 μm.

The conclusion that the extrinsic S-stars have little or no circumstellar material is consistent with the evolutionary scenario envisioned for these stars. The mass function of the extrinsic S-stars is $Q = M_2^3/(M_1 + M_2)^3 = 0.04–0.05 M_\odot$ (Jorissen & Mayor 1992). For a WD companion of $M_2 = 0.55–0.65 M_\odot$ this puts the extrinsic S-stars at $1.2–1.7 M_\odot$. If it is assumed that that the S-stars have $T_{\rm eff} < 4000$ K to show ZrO (equivalent spectral type $\geq$ M0) and using the new evolutionary tracks of Schaller et al. (1992) I find that for a Reimers law the mass loss rate is $2–10\ 10^{-9}\ M_\odot\ {\rm yr}^{-1}$ on the RGB. If an extrinsic S-star is observed at the tip of the RGB (where the evolution is fastest though) the mass loss rate may be $\sim 3\ 10^{-8}\ M_\odot\ {\rm yr}^{-1}$. The mass loss rate on the AGB is typically 10–1000 times larger than the mass loss rate on the RGB. Given the evolutionary status of the intrinsic and extrinsic S-stars it is not surprising that the infrared properties of the two classes are so different.

Having established the (infrared) criteria by which the intrinsic and extrinsic S-stars can be separated it is interesting to estimate the contamination by extrinsic S-stars in an optically complete sample. In the introduction to his catalog, Stephenson states that it is probably complete upto $V = 10$. Being conservative, I selected all S-stars with $V < 9$ from the Stephenson (1984) catalog and cross correlated them with the PSC. Of the 66 stars, 13 have Tc and 23 have no Tc. To the remaining 30 I applied my infrared selection criteria. I find that 8 are intrinsic S-stars, 11 are extrinsic and for the remaining 11 the infrared criteria are not conclusive. The last category consists mainly of stars with low 12 μm fluxes for which there is no LRS spectrum available. I conclude that in an optical complete sample of S-stars, between 50% and 70% are extrinsic stars.

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