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# Accretion from circumstellar discs and the $\lambda$ Boo phenomenon

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**ABSTRACT**

This paper examines the suggestion by Venn & Lambert that the $\lambda$ Boo phenomenon may be caused by accretion of depleted circumstellar gas. The *IRAS* data base was searched for sources corresponding to those in a catalogue of over 100 $\lambda$ Boo candidates. A relatively small fraction ($<20$ per cent) of the catalogue stars that were detected by *IRAS* show infrared excesses like those seen in other early-type stars. However, this is expected, due to non-genuine $\lambda$ Boo entries in the catalogue and finite circumstellar disc lifetimes. Additionally, it is argued that the amount of accreted depleted gas required to cause $\lambda$ Boo abundance patterns is so small that any associated dust is not *necessarily* detectable by thermal emission in the infrared or submillimetre regions. The proportions of bona fide and non-$\lambda$ Boo stars showing infrared excesses differ at the 84 per cent confidence level, which is only suggestive evidence for accretion. A simple model, where accretion of depleted gas once in a circumstellar disc's 'central hole' occurs, gives accretion rates and masses consistent with semi-empirical values inferred from observed abundances in $\lambda$ Boo stars. These values are, however, only weakly constrained. The accretion rates are also consistent with Charbonneau's independent estimate.

**Key words:** accretion, accretion discs – stars: chemically peculiar – circumstellar matter.

## 1 INTRODUCTION

First discriminated by Morgan, Keenan & Kellman (1943), $\lambda$ Boo stars are chemically peculiar, early-type stars characterized by weak metallic lines, rapid rotation ($\sim 100$ km s$^{-1}$) and Population I kinematics. Michaud & Charland (1986) argued that diffusion in the presence of mass loss produces underabundances consistent with those observed in $\lambda$ Boo stars. Faraggiana, Gerbaldi & Böhm (1990, hereafter FGB) have suggested criteria from UV spectra to recognize $\lambda$ Boo stars. Renson, Faraggiana & Böhm (1990, hereafter RFB) have produced an extensive catalogue of all objects that have been classified at one time as $\lambda$ Boo stars. Several authors have noted that some $\lambda$ Boo stars have far-infrared excesses.

Venn & Lambert (1990, hereafter VL) found that abundances in the $\lambda$ Boo stars they observed resembled those of depleted interstellar gas, and they proposed that the $\lambda$ Boo phenomenon might be due to accretion of circumstellar gas having interstellar abundances. Because a few $\lambda$ Boo stars demonstrate infrared (IR) excesses, VL conjectured that circumstellar grains associated with this gas should be detectable. Charbonneau (1991) has proposed a simple model to explain the observed abundances in $\lambda$ Boo stars in terms of accretion and chemical separation. He finds a narrow range of accretion rates near $\sim 10^{-13}$ M$_\odot$ yr$^{-1}$ is able to reproduce observed abundances and account for the range in spectral type of $\lambda$ Boo stars.

These intriguing suggestions merit investigation of *IRAS* observations of $\lambda$ Boo stars. This is done in Sections 2 and 3 with the RFB catalogue, which contains over 100 objects. Section 4 discusses the implications of the *IRAS* results for the accretion hypothesis. In Sections 5 and 6, a specific variation of the VL hypothesis is examined: that the proposed accreted gas in Vega's atmosphere once resided in the surrounding central hole thought to be depleted now of material (at least of sizes $a<1$ mm). Section 7 discusses the results of models invoking diffusion to explain the $\lambda$ Boo phenomenon in the light of our own results. Section 8 summarizes the conclusions reached here and suggests future work.

## 2 *IRAS* DATA

### 2.1 Source identification

The second version of the *IRAS* Point Source Catalog (PSC2), the Serendipitous Survey Catalog (SSC) and the

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Faint Source Catalog (FSC) were searched for entries corresponding to objects in the RFB catalogue of $\lambda$ Boo candidates. SAO coordinates were taken from the SIMBAD data base and checked for corresponding entries in the PSC2, SSC and FSC within twice the brightness-dependent positional uncertainties. Only five of the 56 detected objects' *IRAS* positions deviated by more than one positional uncertainty from the optical positions. These stars are marked in the notes of Table 1 with asterisks.

The nature of these five sources was investigated further. A search of the SIMBAD data base and NASA Extragalactic Database (NED) revealed no association with extragalactic sources. An ADDSCAN/SCANPI request was made to the Infrared Processing and Analysis Center (IPAC) for the three most discrepant sources (HD 36496, 39421 and 79108). ADDSCANS were requested at points in a grid surrounding the known stellar position and the Faint Source Catalog position. For each position, attention was restricted to the scan-type producing the maximum S/N ratio. In most cases this was the noise-weighted, co-added (code 1003) scans. At several grid points, though, the median (code 1002) was used. The FWHM of the fitted template, *W50*, indicated that all the sources were point-like. Source positions were determined from peak emission at 12 μm.

The positions (equinox 1950.0, epoch 1985.5) determined from the ADDSCANS are RA$=05^{\mathrm{h}}32^{\mathrm{m}}08\overset{\mathrm{s}}{.}5$, Dec.$=+66°39'56''$ for F05230+6639; RA$=05^{\mathrm{h}}49^{\mathrm{m}}44\overset{\mathrm{s}}{.}5$, Dec.$=-09°03'11''$ for F05497−0903; and RA$=09^{\mathrm{h}}09^{\mathrm{m}}35\overset{\mathrm{s}}{.}5$, Dec.$=+04°04'36''$ for F09095+0404. Positional uncertainties were calculated using the precepts in §II of the *IRAS* Faint Source Survey Explanatory Supplement (version 2, Moshir et al. 1992). They are close to the values given in the FSC itself. Use of the proper-motion-corrected SAO coordinates for the sources' potential stellar counterparts reveals that F05230+6639 is almost coincident (within 2 arcsec) with HD 36496. It is also found that F05497−0903 is practically coincident with HD 39421. The ADDSCAN position for F09095+0404 is displaced from HD 79108 by ~16 arcsec, but this deviation is only at the $\sim 0.5\sigma$ level, given the uncertainties.

Given these positional associations and the lack of any correspondence between the FSC sources and extragalactic objects, it seems likely that the *IRAS* sources with asterisks in Table 1 correspond to real stellar detections. Indeed, it is surprising that more of the sources do not deviate at $\geq 1\sigma$ level from the stellar positions. For ordinary Gaussian confidence intervals, one would expect roughly a third of the sample to do so. Note that, even if all of the five objects with asterisks in Table 1 are not genuine stellar sources, the main conclusion of this paper that there is suggestive evidence of a connection between IR excesses and the $\lambda$ Boo phenomenon would not be affected: three show no excesses at all. One of the remaining two has no definitely positive or negative $\lambda$ Boo designation. The final source (HD 130158) has a negative $\lambda$ Boo designation. Therefore, if the IR excess found here for it were spurious, our main conclusion would actually be strengthened.

### 2.2 Fluxes and IR excess calculation

Flux densities were converted to magnitudes, using the *IRAS* definition of 0.0 magnitude in each (12, 25, 60 and 100 μm) bandpass. Colour corrections (given in the *IRAS* Explanatory Supplement) corresponding to a 10 000-K blackbody were applied. For those bands $\lambda_i$ ($\lambda_i = 12$, 25, 60 and 100 μm) where a flux was available, the colour index $(V-\lambda_i)_{\mathrm{o}}$ was computed. No extinction corrections were applied to the values of $V$ or $\lambda_i$, due to great uncertainties in the spectral type versus $(B-V)$ relation for peculiar stars and in the spectral classification of rapidly rotating, early-type stars. Our objects are mainly bright stars for which extinction is negligible (see Waters, Coté & Aumann 1987).

Waters et al. (1987) determined an empirical relation between $(B-V)$ and $(V-12$ μm$)$ for 'normal' stars of most spectral types. The $(B-V)$ of an RFB $\lambda$ Boo candidate yields a predicted colour, $(V-12\ \mu\mathrm{m})_{\mathrm{p}}$. It was assumed that the predicted far-IR colours are solar, $(12\ \mu\mathrm{m}-25\ \mu\mathrm{m}) = (25\ \mu\mathrm{m}-60\ \mu\mathrm{m}) = -0.03$ and $(60\ \mu\mathrm{m}-100\ \mu\mathrm{m}) = -0.06$, allowing one to derive corresponding predicted colours $(V-25\ \mu\mathrm{m})_{\mathrm{p}}$, $(V-60\ \mu\mathrm{m})_{\mathrm{p}}$, and $(V-100\ \mu\mathrm{m})_{\mathrm{p}}$. The difference between the observed and predicted colour indices, $(V-\lambda_i)_{\mathrm{o}}-(V-\lambda_i)_{\mathrm{p}}$, is the colour excess in each *IRAS* band $\lambda_i$.

## 3 *IRAS* RESULTS

Table 1 lists the *IRAS* data. Columns (1) and (2) give the HD number and *IRAS* source identification (F=FSC, P=PSC2, S=SSC). Column (3) is an evaluation of the $\lambda$ Boo classification. A 'Y' indicates those stars listed as 'best candidates' by RFB, stars classified as $\lambda$ Boo by FGB, or those objects studied by VL. An 'N' indicates the most doubtful $\lambda$ Boo classifications according to RFB and FGB. An 'E' indicates the star is significantly evolved according to consistent luminosity classifications in the literature; for these stars, chemical peculiarities or IR excesses may not be associated with the $\lambda$ Boo phenomenon and they are considered no further. Column (4) gives the predicted $(V-12)$ colour, while the next four columns give the colour excess and $1\sigma$ uncertainty (in mag) in each *IRAS* band. Two stars noted as binaries have close companions with inadequate optical data to derive reliable predicted magnitudes, and have later type companions which may cause their IR excesses; these objects are eliminated from further consideration.

Table 2 lists data for objects considered as doubtful *IRAS* detections. Source P04136+6147 probably corresponds to SAO 13087 and not SAO 13086 = HD 26801. Other *IRAS* source positions are very discrepant (see notes) with the $\lambda$ Boo candidate optical coordinates and will not be considered further. The sources are listed because they apparently have no optical counterparts within a few arcmin of the *IRAS* position, except for the RFB candidates listed in column (1).

Table 1 indicates that six stars demonstrate significant IR excesses in at least one *IRAS* band: HD 31295, 79108, 125162, 130158, 161868 and 172167. There is marginal evidence (at the $\sim 2\sigma$ level) for excesses in four others: HD 111604, 150177, 168151 and 188728. IR excesses in the context of a $\lambda$ Boo classification have not been noted before for HD 79108, 130158, 161868, or the four marginal IR-excess stars. Confirmation of their uncertain $\lambda$ Boo classification with high-dispersion optical spectroscopy or *IUE* spectra would be of great interest. The excesses displayed by these stars are not unlike those previously noted for other

**Table 1.** *IRAS* detections of λ Boo candidates.

| HD | IRAS | λ Boo | (V-12)$_p$ | Δ(V-12) | Δ(V-25) | Δ(V-60) | Δ(V-100) | Notes |
|---|---|---|---|---|---|---|---|---|
| 11413 | F01489-5027 | | 0.46 | 0.10 (0.12)- | - | - | | |
| 16811 | F02395+1947 | | -0.01 | -0.22 (0.17) | - | - | - | |
| 21335 | F03241+1834 | | 0.492 | 0.16 (0.17) | - | - | - | |
| 22470 | F03340-1737 | N | -0.38 | -0.07 (0.11) | - | - | - | |
| 24712 | P03529-1214 | N | 0.93 | -0.07 (0.11) | - | - | - | |
| 31295 | P04521+1004 | Y | 0.32 | -0.05 (0.12) | - | 3.03 (0.16) | - | |
| 36496 | F05320+6639 | | 0.73 | -0.08 (0.11) | - | - | - | $^*$1.53σ |
| 39283 | P05506+5541 | N | 0.20 | 0.05 (0.07) | - | - | - | |
| 39421 | F05497-0903 | | 0.35 | -0.25 (0.15) | - | - | - | $^*$1.37σ |
| 56405 | P07139-1529 | | 0.292 | -0.34 (0.11) | - | - | - | |
| 78316 | F09050+1052 | N | -0.31 | 0.02 (0.16) | - | - | - | |
| 78661 | F09070+1146 | | 1.03 | 0.15 (0.12) | - | - | - | |
| 79108 | F09095+0404 | | 0.02 | 0.20 (0.17) | - | 3.57 (0.26) | - | $^*$1.74σ |
| 79469 | P09117+0231 | N | -0.13 | 0.09 (0.16) | - | - | - | |
| 80081 | P09157+3700 | | 0.23 | 0.06 (0.07) | - | - | - | |
| 84123 | F09409+4216 | | 0.85 | 0.10 (0.17) | - | - | - | |
| 89353 | P10158-2844 | E | 0.73 | 4.78 (0.07) | 4.64 (0.07) | 4.80 (0.11) | - | |
| | S10158-2844 | | 0.73 | 4.54 (0.07) | 4.78 (0.07) | 4.88 (0.09) | 5.68 (0.13) | |
| 91324 | P10293-5327 | | 1.35 | -0.03 (0.07) | 0.24 (0.19) | | - | - |
| 98353 | P11164+3827 | | 0.41 | -0.13 (0.07) | - | - | - | |
| 110411 | P12394+1030 | Y | 0.32 | -0.01 (0.15) | - | - | - | |
| 111604 | P12477+3747 | | 0.49 | 0.23 (0.11) | - | - | - | |
| 111786 | F12492-2627 | Y | 0.71 | -0.27 (0.15) | - | - | - | |
| 111893 | F12499+1623 | | 0.52 | -0.03 (0.19) | - | - | - | |
| 113848 | P13039+2125 | | 1.08 | 0.16 (0.11) | - | - | - | |
| 119288 | P13397+0838 | | 1.17 | -0.18 (0.11) | - | - | - | |
| 123299 | P14030+6436 | | -0.11 | 0.04 (0.07) | -0.10 (0.11) | - | - | |
| 125162 | P14144+4619 | Y | 0.29 | 0.01 (0.07) | 0.37 (0.12) | 2.64 (0.12) | - | |
| 125276 | P14161-2535 | | 1.35 | 0.13 (0.07) | - | - | - | |
| 128167 | P14325+2957 | | 1.05 | -0.11 (0.07) | -0.05 (0.15) | - | - | |
| 130158 | F14444-2524 | N | -0.14 | -0.01 (0.20) | - | 3.35 (0.26) | - | $^*$1.08σ |
| 141851 | P15486-0256 | | 0.41 | -0.04 (0.11) | - | - | - | |
| 142703 | F15537-1441 | E | 0.71 | 0.21 (0.10) | - | - | - | |
| 149303 | P16302+4542 | | 0.41 | -0.34 (0.12) | - | - | - | |
| | S16303+4542 | | 0.41 | -0.05 (0.14) | - | - | - | |
| 150177 | P16369-0927 | | 1.30 | 0.33 (0.15) | - | - | - | |
| 160928 | P17411-4242 | | 0.52 | 0.05 (0.19) | - | - | - | |
| 161868 | P17453+0243 | | 0.17 | -0.11 (0.07) | 0.40 (0.11) | 3.39 (0.11) | - | |
| | S17454+0243 | | 0.17 | -0.12 (0.07) | 0.46 (0.07) | 3.37 (0.09) | - | |
| 168151 | P18136+6422 | | 1.10 | 0.15 (0.07) | 0.16 (0.11) | - | - | |
| 168740 | F18207-6302 | | 0.63 | -0.01 (0.12) | - | - | - | |
| 169022 | P18208-3424 | N | -0.06 | 0.17 (0.08) | 0.25 (0.12) | 0.88 (0.16) | - | Evolved |
| | S18208-3424 | | -0.06 | 0.17 (0.07) | 0.26 (0.07) | 0.60 (0.09) | - | |
| 170680 | P18285-1826 | | 0.05 | -0.05 (0.08) | - | - | - | |
| 172167 | P18352+3844 | Y | 0.05 | -0.01 (0.07) | 0.17 (0.07) | 1.75 (0.12) | 3.01 (0.12) | |
| | S18352+3844 | | 0.05 | -0.10 (0.07) | 0.18 (0.07) | 2.03 (0.09) | 3.24 (0.13) | C05 |
| | S18352+3844 | | 0.05 | 0.00 (0.07) | 0.25 (0.07) | 2.00 (0.09) | 3.21 (0.13) | D05 |
| | S18352+3844 | | 0.05 | -0.05 (0.07) | 0.22 (0.07) | 2.04 (0.09) | 3.20 (0.13) | E05 |
| 181470 | F19172+3721 | E | -0.05 | -0.04 (0.19) | - | - | - | |
| 187949 | F19503-1444 | N | 0.46 | 0.42 (0.12) | - | - | - | binary, see text |
| 188728 | P19539+1117 | N | 0.05 | 0.38 (0.19) | - | - | - | |
| 192640 | P20126+3639 | Y | 0.46 | -0.01 (0.07) | - | - | - | |
| 193281 | F20173-2921 | | 0.55 | 0.52 (0.17) | - | - | - | binary, see text |
| 198160 | P20474-6237 | | 0.55 | -0.03 (0.11) | - | - | - | |
| 203608 | P21223-6535 | | 1.33 | 0.04 (0.07) | 0.01 (0.11) | - | - | |
| | S21223-6534 | | 1.33 | -0.13 (0.07) | -0.03 (0.07) | - | - | |
| 204041 | F21233+0019 | | 0.52 | -0.12 (0.23) | - | - | - | $^*$1.27σ |
| 210418 | P22076+0557 | | 0.26 | 0.03 (0.07) | 0.14 (>0.47) | - | - | |
| 210111 | F22058-3322 | | 0.63 | 0.14 (0.13) | - | - | - | |
| 212061 | P22190-0138 | N | -0.14 | -0.13 (0.12) | - | - | - | |
| 217782 | P23002+4229 | N | 0.32 | -0.05 (0.11) | - | - | - | |
| 220061 | P23181+2327 | | 0.55 | -0.02 (0.11) | - | - | - | |
| 220278 | P23200-1518 | | 0.63 | 0.02 (0.11) | - | - | - | |
| 221756 | P23321+3957 | | 0.35 | 0.07 (0.20) | - | - | - | |

**Table 2.** Doubtful *IRAS* detections.

| HD | IRAS | $\lambda$ Boo | $(V-12)_p$ | $\Delta(V-12)$ | $\Delta(V-25)$ | $\Delta(V-60)$ | $\Delta(V-100)$ | Notes |
|---|---|---|---|---|---|---|---|---|
| 26801 | P04136+6147 | | 0.05 | -0.07 (0.11) | - | - | - | 0.9$\sigma$ |
| 109738 | P12348-6734 | | 0.55 | 3.80 (0.07) | 4.61 (0.11) | - | - | 3.9$\sigma$ |
| 154153 | P17026-4402 | E | 0.84 | 1.51 (>0.22) | 2.64 (0.20) | - | - | 7.9$\sigma$ |
| 193063 | P20152+3932 | | -0.11 | >3.94 (0.15) | 5.43 (0.20 | 10.22 (0.11) | >13.01 (0.15) | 5.7$\sigma$,binary |
| 193256 | P20168-2922 | | 0.41 | 2.59 (0.11) | - | - | - | 6.9$\sigma$,binary |
| 193281 | P20168-2922 | | 0.83 | 0.90 (0.11) | - | - | - | 6.9$\sigma$,binary |
| 201019 | P21043-5529 | | 0.98 | - | - | 6.05 (0.11) | - | 7.7$\sigma$ |

early-type (B, A and F) stars (Coté 1987; Patten & Willson 1991). These excesses are thought to be due to thermal radiation from circumstellar dust (Aumann 1985; Coté 1987), although some probably arise from free–free emission from hot, circumstellar gas. No attempt at modelling the 10 sources is made here. For several of the stars the wavelength coverage of the spectral energy distributions is sparse or non-existent in the IR and far-IR. Additionally, there is some uncertainty in accurately determining the temperature of potential chemically peculiar stars. Where the data permit, however, the reader can gather an idea of the range of allowed dust disc temperatures and sizes by utilizing figs 2(a) and (b) of Coté (1987), who gives best-fitting parameters for HD 172167 and 161868.

Excluding the evolved and binary stars, the six stars represent 13.0 ± 5.0 per cent of the sample detected by *IRAS*. The uncertainty is just the $1\sigma$ value expected from sampling a binomial distribution.[1] Inclusion of the four marginal IR-excess stars implies that 20 ± 5.7 per cent of the sample detected by *IRAS* demonstrates an IR excess in at least one *IRAS* band.

## 4 IMPLICATIONS FOR ACCRETION

The above results, indicating that $\leq 20$ per cent of the $\lambda$ Boo candidates detected by *IRAS* show IR excesses, imply one or more of the following: (a) many stars in our sample are not true $\lambda$ Boo stars; (b) the circumstellar dust dissipation time-scale is small, so that only the youngest stars exhibit IR excesses; (c) VL's suggestion is incorrect, and there is not significant circumstellar material around $\lambda$ Boo stars; and (d) accreted gas leads to underabundances, but there is not enough dust to be detected by *IRAS*.

Definition of the $\lambda$ Boo class is difficult, and this has hampered efforts to determine its origin (FGB). Only 12 of 32 objects (37.5 ± 8.6 per cent) in the RFB catalogue can be considered definite $\lambda$ Boo stars according to evaluations cited in Section 3. Contamination of our original sample with non-$\lambda$ Boo stars can partly explain the small proportion (which otherwise might be taken as evidence against the accretion hypothesis) of IR-excess objects.

Recent estimates of circumstellar disc dissipation time-scales are $\sim 10^7$ yr (e.g. Skrutskie et al. 1990). This time-scale is relevant for the warmer, inner parts of the disc, where near-IR ($\sim$10-μm) excesses are observed. Time-scales for dissipation of the cooler, outer parts of circumstellar discs are only weakly constrained at $\leq 3 \times 10^8$ yr (Skrutskie et al. 1991). Since the main-sequence lifetime for a typical $\lambda$ Boo object is $\leq 10^9$ yr, $\leq 30$ per cent of the RFB objects would be expected to show IR excesses due to circumstellar material (assuming a random age distribution).

Patten & Willson (1991) investigated IR excesses in stars with a range in spectral types similar to the $\lambda$ Boo stars. Their results indicate that 19.9 ± 2.0 per cent (where the uncertainty is that expected from sampling a binomial distribution) of the single, main-sequence stars in their sample showed an excess. Using this result (instead of the upper limit in the previous paragraph) and the estimate of non-$\lambda$ Boo contamination in the RFB catalogue, only 7.5 ± 1.9 per cent of our sample would be expected to demonstrate IR excesses if the accretion hypothesis were valid. This proportion is not statistically different from the observed fraction, 13 per cent, of excesses. The small fraction of $\lambda$ Boo objects observed to have IR excesses is *not* inconsistent with the accretion hypothesis.

One can now examine the accretion hypothesis directly by considering only the bona fide and non-$\lambda$ Boo stars in our sample. Three of the six (50 ± 20 per cent) stars in Table 1 with a 'Y' designation show an IR excess in at least one *IRAS* band. One of the eight 12.5 ± 11.7 per cent) stars with a 'N' designation (excluding the evolved stars and the two binaries) shows an IR excess. These proportions seem dissimilar, but an exact treatment of 2 × 2 contingency tables (Fisher 1954) shows that the null hypothesis of an equal proportion of bona fide and non-$\lambda$ Boo stars showing IR excesses can only be excluded at the 84 per cent confidence level. The three bona fide $\lambda$ Boo stars not exhibiting an IR excess have data only at 12 μm. The flux density upper limits in other bands are not low enough to exclude excesses. Far-IR observations to determine excesses or optical/UV spectroscopic observations to confirm the $\lambda$ Boo classification may be needed for only a few more stars to be able to exclude more firmly the null hypothesis or the accretion hypothesis. The current evidence is only suggestive of a link between the $\lambda$ Boo phenomenon and circumstellar material. Alternative (d) from above is discussed in the next section.

## 5 A SIMPLE ACCRETION MODEL

Detailed modelling of early-type stars showing IR excesses has revealed that central holes are common features of circumstellar discs. These holes are usually (although not always) characterized by small near-IR (at 12 and 25 μm, say) excesses from optically thin areas in the inner disc and large far-IR (at 60 and 100 μm) excesses in the outer regions. Skrutskie et al. (1990) note that, in a disc similar to the solar

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[1] Use of a binomial distribution requires that the four stars with marginal IR-excess classifications be subtracted from the sample size to calculate the mean and uncertainty.

nebula, different IR wavelengths probe different physical regions of the disc. By comparing the spectral energy distributions (in the $\lambda F_\lambda$ versus $\lambda$ plane, say) with those expected from disc models and stellar photospheres, the presence of central holes can be betrayed by revealing optically thin regions of the discs (see figs 1 and 4 of Skrutskie et al. 1990).

Comparison of, e.g., fig. 4 of Skrutskie et al. (1990) can be made with Fig. 1, which shows the spectral energy distributions of our 10 stars that demonstrate possible IR excesses. The filled squares are the observational data (*IRAS* fluxes plus other photometry from the literature). The solid line is a blackbody curve for a temperature of 8500 K, which is typical of the objects found here. For HD 150177 and 168151, the blackbody curves are for temperatures of 6350 and 6700 K, which are more reasonable estimates of the stellar photospheric effective temperatures for these stars. It is emphasized that no detailed fitting to the optical or near-IR data has been done, and a photospheric temperature of 8500 K is not precisely applicable to all the stars. The reader should therefore rely on Table 1 to determine the magnitude of IR excesses at *IRAS* wavelengths; Fig. 1 will supply only an approximate visual estimate. Most stars in the figure lack sufficient data for comparison with disc models in order to infer the presence of central holes. However, none of the six stars exhibiting certain IR excesses apparently does so at 12 μm. This may not be inconsistent with the existence of such central holes for our sources – only additional data and modelling will be able to tell.

Because such 'central holes' apparently characterize circumstellar discs surrounding stars of ages $\geq 10^7$ yr (e.g. Skrutskie et al. 1990), they may represent previous reservoirs of material that could be accreted on to central stars. One can consider this possibility by demanding consistency between the mass of gas accreted by a λ Boo star and that available in the circumstellar reservoir. Equivalently, using a gas-to-dust ratio, the mass of dust in the surrounding material and that once associated with the accreted gas can be compared. The latter approach is utilized here, since *IRAS* and submillimetre studies give estimates of dust mass for particles with sizes $a \leq 1$ mm.

Consider a star surrounded by a circular region of radius $r_1$ devoid of observable material. An annulus with inner and outer edges of $r_1$ and $r_2$ represents a circumstellar disc with *assumed* constant thickness. The mass, $M_\mathrm{d}$, in this annulus is given by

$$M_\mathrm{d} = \int_{r_1}^{r_2} 2\pi r n(r)\,\mathrm{d}r,$$

where $n(r)$ is the adopted density distribution given by $n(r) = Cr^{-\alpha}$. The value of $M_\mathrm{d}$ determined by submillimetre and IR observations is a lower limit to the true disc mass because of possible undetected large particles (e.g. planets). $M_\mathrm{d}$, or a lower limit, is given by Becklin & Zuckerman (1990) for both Vega and $\beta$ Pic from submillimetre observations. These two stars are considered, since they have been subject to detailed modelling by others, and because Vega is almost certainly a ('mild') λ Boo star (VL) and $\beta$ Pic has recently been suggested to be a λ Boo star (King & Patten 1992). Values of $r_1$ and $r_2$ were taken from the models in Gillett (1985) and Artymowicz, Burrows & Paresce (1989). For $\beta$ Pic, a larger outer radius, 500 au, than the one of 400 au given in the reference was adopted.

Although there is uncertainty in the value of $\alpha$, it probably lies in the range 1–3 (Nakano 1991). Following the discussion in Nakano (1991), a value of $\alpha = 1$ is assumed; this seems reasonable for the inner disc regions and avoids divergence of the mass. Also, $\alpha = 1$ is expected for dust grains in equilibrium, as enforced by the Poynting–Robertson effect (Nakano 1991). One can then solve for the constant $C$ and determine the dust mass, $M_\mathrm{h}$, that was once present in the central 'hole':

$$M_\mathrm{h} = C \int_0^{r_1} 2\pi r r^{-1}\,\mathrm{d}r.$$

Table 3 gives the values of $M_\mathrm{d}$ from Becklin & Zuckerman (1990), the adopted values of $r_1$ and $r_2$, and the calculated values of $M_\mathrm{h}$ (or lower limits) for Vega and $\beta$ Pic ($1.6 \times 10^{24}$ and $5.6 \times 10^{24}$ g).

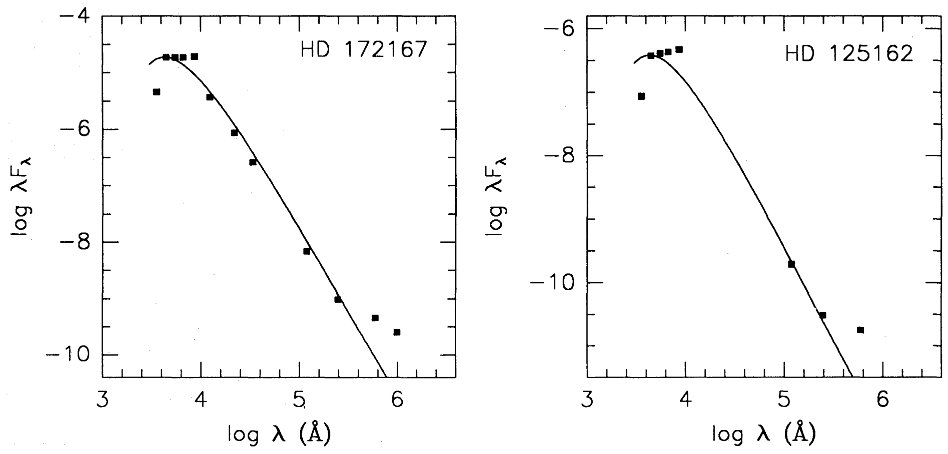

**Figure 1.** Spectral energy distributions (filled squares) of the 10 stars in our sample that apparently show IR excesses. The abscissa is the logarithm of wavelength in Å. The ordinate is the logarithm of the flux in erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The solid lines represent flux from a blackbody having a temperature of 8500 K (except for HD 150177 and 168151, where the curves are for temperatures of 6350 and 6705 K). The passbands for the data points are (for Vega, from left to right on the plot) *U*, *B*, *V*, *R*, *I*, *J*, *K*, *L*, 12 μm, 25 μm, 60 μm and 100 μm.

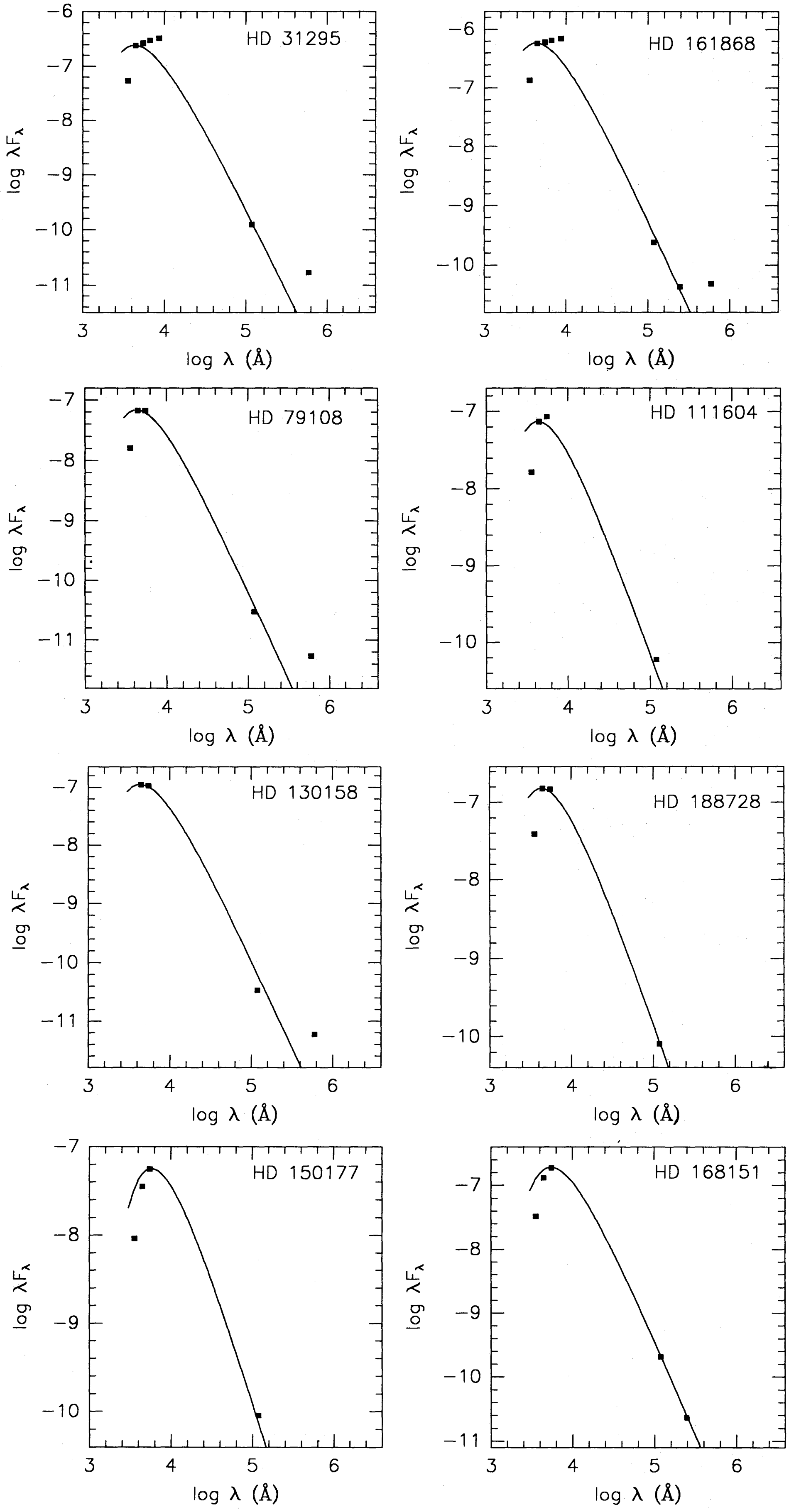

Figure 1 – *continued*

**Table 3.** Model parameters and results.

| Star | $M_d$ (g) | $r_1$ (AU) | $r_2$ (AU) | $M_h$ (g) | $M_a$ (g) | $M_p$ (g) | $M_{le}$ (g) |
|---|---|---|---|---|---|---|---|
| Vega | $7.3 \times 10^{24}$ | 30 | 170 | $1.6 \times 10^{24}$ | $6.1 \times 10^{20}$ | $3.9 \times 10^{28}$ | $2.4 \times 10^{30}$ |
| β Pic | $1.8 \times 10^{26}$ | 15 | 500 | $5.6 \times 10^{24}$ | $1.5 \times 10^{21}$ | $3.9 \times 10^{28}$ | $1.2 \times 10^{30}$ |

The amount of accreted gas can be estimated from the fraction, $f$, of interstellar gas required to produce the observed abundance patterns as given by VL. This estimate requires knowledge of how deep the gas is mixed in the stellar atmosphere. This mass is calculated above the point where the visual continuum of VL's spectra is formed; because the gas may be mixed deeper, this estimate is only a lower limit. For Vega, the 9500-K, $\log g = 4$, one-tenth solar abundance model atmosphere of Kurucz (1979) was used. The 5000-Å optical depth is equal to one at a value of $\sim 0.23$ g cm$^{-2}$. The radius of an A0V star from Allen (1973) gives an atmospheric mass of $\sim 6.1 \times 10^{22}$ g in accreted interstellar gas. Adoption of a canonical interstellar dust-to-gas ratio of 0.01 gives $6.1 \times 10^{20}$ g in dust originally associated with the accreted gas. The calculation is repeated for $\beta$ Pic using the 8000-K, $\log g = 4$, one-tenth solar abundance model of Kurucz to determine the mass cross-section, an adopted radius for an A5V star, an interstellar fraction of the atmospheric gas $f = 0.85$ (typical for the four objects studied by VL), and the above dust-to-gas ratio. The result is an associated dust mass of $1.5 \times 10^{21}$ g. These values are listed as $M_a$ in Table 3.

For Vega, $M_h$ is some four orders of magnitude larger than $M_a$, so that there is enough depleted, circumstellar gas in our disc model to produce λ Boo abundance anomalies. The value of $M_a$ for Vega, $\sim 10^{21}$ g, is four orders of magnitude less than the mass of material detected around Vega by Becklin & Zuckerman (1990), two orders of magnitude less than their detection limits, and seven orders of magnitude less than the lowest disc masses found by Beckwith et al. (1990). The amount of depleted gas needed to alter the photospheric abundances is so small that the associated mass of dust may be below *IRAS* and ground-based submillimetre detection limits. Contrary to VL's proposal, the circumstellar dust once associated with accreted gas is not necessarily detectable in the IR (or submillimetre). Possibility (d) from Section 4 may bias the observed fraction of λ Boo stars with IR excesses, and this effect is difficult to quantify.

## 6 FURTHER CONSTRAINTS ON THE ACCRETION MODEL

As mentioned before, the two dust masses ($M_h$ and $M_a$) are both likely to be lower limits. Upper limits to the dust mass in the central hole and that implied by photospheric abundances would be useful. Material in central holes could be in particles of sizes $a \gg 1$ mm (i.e. planets or planetesimals). A reasonable upper estimate of the central-hole dust mass is the mass of material in our Solar system. This mass ($M_p \sim 3.9 \times 10^{28}$ g), estimated by summing the masses of the terrestrial planets and $\sim 1$ per cent of the gas giants (making no corrections for possible augmentation), is listed in Table 3.

An upper estimate of the mass of accreted gas in λ Boo atmospheres could be made if the maximum depth to which gas was mixed in the stellar atmosphere was known. Light-element (Li, Be and B) abundances give information about how deeply material is mixed, as these elements are destroyed by (p, $\alpha$) reactions at temperatures of a few $\times 10^6$ K. Light-element abundances for RFB objects and the ISM are shown in Table 4. Vega (HD 172167) is the only object which is a definite λ Boo object. RFB consider HD 207978 to be a misclassified λ Boo star. While the data are sparse, the observed abundances are generally consistent with the ISM abundance, as found by VL for other elements. Light elements have not been totally destroyed in these atmospheres, so material does not appear to be thoroughly mixed down to $T \sim$ few $\times 10^6$ K. Using the models of Iben (e.g. Iben 1967), this occurs at a depth where the overlying mass of accreted ISM gas would be $\sim 2.4 \times 10^{32}$ g for Vega and $\sim 1.2 \times 10^{32}$ g for $\beta$ Pic. The dust mass associated with this accreted gas is $\sim 2.4 \times 10^{30}$ and $\sim 1.2 \times 10^{30}$ g for Vega and $\beta$ Pic, respectively, and is listed as $M_{le}$ in Table 3.

For Vega, the dust mass associated with the accreted interstellar gas mass inferred from observed abundances is bounded by $M_a$ and $M_{le}$:

$$6 \times 10^{20} \leq M \leq 2 \times 10^{30} \text{ g}.$$

The range in dust mass inferred once to have been (or still to be) in the central hole is given by $M_h$ and $M_p$:

$$2 \times 10^{24} \leq M \leq 4 \times 10^{28} \text{ g}.$$

These ranges are not incompatible with each other. The best estimates of the simple accretion model fall between the semi-empirical limits satisfying the observed abundances. However, it should be emphasized that the current constraints are very weak. $M_{le}$ is likely to be an overestimate, and the Solar system mass of material occupying Vega's central hole is a gross assumption.

## 7 OTHER MODELS

Michaud & Charland (1986) investigated diffusion in the presence of mass loss in early-type stars and found that, for a mass-loss rate of $10^{-13}$ M$_\odot$ yr$^{-1}$, chemical separation can cause underabundances by a factor of $\sim 3$. Charbonneau (1991) finds a critical $v \sin i$ of $\sim 200$ km s$^{-1}$ for which the combined diffusion, accretion and circulation velocity vanishes in the polar regions at the base of the outer convection zone. His calculations indicate that diffusion in the presence of mass loss and meridional circulation does *not* lead to underabundances during main-sequence evolution – even for $v \sin i$ well below the critical value. His model for diffusion in the presence of *accretion* can produce underabundances if the accretion rate is between $5 \times 10^{-14}$ and $5 \times 10^{-13}$

**Table 4.** Light-element abundances of λ Boo candidates.

| HD # | ε(Li) | Be/H | B/H | Reference |
|---|---|---|---|---|
| 91324 | 2.12 | - | - | 1,2 |
| 113848 | 3.00 | - | - | 3 |
| 119288 | <1.00 | - | - | 3 |
| 123299 | - | $<5.0 \times 10^{-11}$ | $2.0 \times 10^{-10}$ | 4,5 |
| 128167 | <1.51 | $<5.5 \times 10^{-13}$ | - | 6,7 |
| 150177 | 2.20 | - | - | 3 |
| 168151 | <1.28 | - | - | 3 |
| 172167 | - | $<4.0 \times 10^{-12}$ | $1.5 \times 10^{-10}$ | 8,9 |
| 203608 | 2.30 | - | - | 10 |
| 207978 | <1.1 | - | - | 3,11 |
| ISM | 2.3-3.0 | $<5 \times 10^{-12}$ | $1\text{-}2 \times 10^{-10}$ | 12,13,14 |

References: (1) Soderblom (1985); (2) Balachandran (1990); (3) Boesgaard & Tripicco (1986); (4) Boesgaard et al. (1982); (5) Boesgaard & Heacox (1978); (6) Boesgaard & Lavery (1986); (7) Boesgaard (1990); (8) Griffin & Griffin (1985); (9) Praderie et al. (1977); (10) Maurice, Spite & Spite (1984); (11) Hobbs & Duncan (1987); (12) Hobbs (1984); (13) Boesgaard (1985); (14) York, Meneguzzi & Snow (1982).

$\mathrm{M}_\odot\ \mathrm{yr}^{-1}$. If these models can uniquely determine the mass-accretion rate and if future submillimetre observations yield estimates of the disc mass, a new estimate of disc dissipation time-scales is possible.

The range of accreted gas mass implied by observed abundances in Vega and its age yield a range of possible gas accretion rates:

$$6 \times 10^{-20} \leq \dot{M} \leq 2 \times 10^{-10}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}.$$

The range of dust masses that once occupied the central hole in our simple accretion model and the age of Vega yield a range of possible gas accretion rates:

$$2 \times 10^{-16} \leq \dot{M} \leq 4 \times 10^{-12}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}.$$

Charbonneau's estimated accretion rate falls within these ranges, and it is encouraging that three independent estimates of the gas-accretion rate are all consistent. Because the simple model proposed here is consistent with the available, but loose, semi-empirical constraints, it is concluded that the accretion hypothesis of VL is a tenable one.

## 8 CONCLUSIONS AND FUTURE WORK

The main conclusions from this investigation are the following. (1) The amount of depleted gas required to cause underabundances in λ Boo stars is small enough that any circumstellar dust associated with this gas is not *necessarily* detectable in the IR or submillimetre regions. (2) Six λ Boo candidates show significant excesses in at least one *IRAS* band; there is marginal evidence for excesses in four others. These data indicate that only a small fraction (≤20 per cent) of stars in the RFB catalogue that were detected by *IRAS* demonstrate IR excesses. However, this is expected from contamination of the catalogue, finite disc lifetimes, and the effects of the first conclusion. It does not, *per se*, argue against the accretion hypothesis. (3) The difference between the proportion of bona fide λ Boo stars and non-λ Boo stars showing IR excesses is significant at the 84 per cent confidence level. This is interpreted as suggestive evidence for accretion. (4) A simple model, in which the depleted gas once resided in a 'central hole', is consistent with semi-empirical constraints provided by λ Boo abundance patterns. The implied accretion rates are not inconsistent with those proposed by Charbonneau (1991).

The accretion hypothesis needs to be investigated further in order to be firmly supported or excluded. Determining whether bona fide λ Boo stars have a significantly larger fraction of IR excesses than other early-type dwarfs will require a two-fold attack. (1) Abundances and/or UV spectra should be obtained for those RFB catalogue stars without a solid classification, as well as for other known Vega-like stars, in order to determine what fraction are λ Boo stars. (2) Several genuine λ Boo stars in the RFB catalogue do not have *IRAS* detections. IR observations (e.g. with *ISO*) or submillimetre observations of these stars are highly desirable. Also, most of our stars lack 25- and 60-μm (where excesses seem best inferred) data. It is important to identify a decoupling mechanism which allows selective accretion of circumstellar, depleted gas. Comparison of evolutionary time-scales implied by the range of λ Boo spectral types and disc dissipation time-scales suggests that the λ Boo phenomenon will arise only in those stars that undergo disc dissipation while on the main sequence. This could be tested, and the time-scale for accretion constrained, by determining abundances in intermediate-mass, pre-main-sequence progenitors of λ Boo stars.

## NOTE ADDED IN PRESS

Cheng et al. (1992) have reported the presence of circumstellar dust around HD 110411 (=HR 4828) based on the *IRAS* FSC and ADDSCAN/SCANPI processing. This star is listed in Table 1 as a bona fide λ Boo object – a designation confirmed by modern spectral classification (Gray 1988) and spectroscopic studies (Sturenburg 1993). However, no IR excess (as determined from the *IRAS* PSC) was found for this star in this paper. Given the IR excess found by Cheng et al. (1992), inclusion of this object in the 2 × 2 contingency table analysis would serve to strengthen significantly the link between IR excesses and the λ Boo phenomenon over and above the level found here. Because the Cheng et al. (1992) analysis increases the sensitivity of *IRAS* data (relative to that in the PSC and FSC alone), a search of the FSC and complementary use of the ADDSCAN/SCANPI software for those objects in Table 1 may result in more IR-excess detections (particularly at 25 and 60 μm) and thus improve the statistics in a 2 × 2 contingency table analysis like that used in this paper.

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