INFRARED OBSERVATIONS OF LATE TYPE STARS

by

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ABSTRACT

Substantative mass-loss resulting in appreciable circumstellar dust envelopes is common in late-type stars. The evolutionary history and physical state of a cool star determine the chemistry within the outer stellar atmosphere mirrored by the molecular and particulate material present in the envelope. The observational consequences of this debri determined by moderate spectral resolution ($\lambda/\Delta\lambda \sim 50$-$100$) infrared spectrophotometry are reviewed. Significant information is provided by observations of the emergent energy flux of both the cool stellar photosphere and of the circumstellar dust envelope. While most of the infrared features observed in late-type stars can be plausibly identified, an as yet unknown emission mechanism marked by strong infrared band structure is known to be operative in a variety of infrared sources. The observed range in shell optical depth in both M and C stars suggests that mass-loss occurs to some degree throughout late stellar evolutionary phases and that occasional periods of high mass-loss are not uncommon.

I. INTRODUCTION

The mapping of pathways followed by stars undergoing post-main-sequence evolution is a task vital to an understanding of the evolutionary history of the matter in our galaxy - whether to be presently aggregated into stars or distributed in the form of gas and dust. During the red giant phase the outer atmosphere becomes greatly distended in response to conditions deep within the stellar interior. Such cool, tenuous, extended envelopes provide ideal conditions for the formation of gaseous molecules and particulate condensates. Apparently appreciable mass is lost by stars throughout post-main-sequence phases, whether by the quasi-steady outflow from both giants and supergiants, the impulse driven expanding shells of planetary nebulae, or the explosive events seen in novae and supernovae. The final evolutionary state of a star - be it white dwarf, neutron star or even black hole - may well be determined by the degree to which the star is able to return mass to the interstellar medium from which it came. The material is returned metal-enriched by nuclei synthesized in the interior and later mixed out, so that the debri provide important clues about stellar structure and nucleosynthesis. Not too surprisingly, these later stages of stellar evolution are often veiled from exploration by standard optical techniques when dust condensation in the ejected material modifies the radiation field of the central star through extinction and thermal re-emission. Stars undergoing extensive mass loss tend to become infrared rather than optical sources. Radio maser line and continuum emission from the ejected molecular clouds is not uncommon. Thus the study of mass loss, late stellar evolution and nucleosynthesis as interdependent phenomena requires definitive infrared observations.

Present difficulties in developing a cohesive theoretical understanding of the process of late stellar evolution (including possible alternative pathways) have been exacerbated by a dearth of hard observational evidence to provide the necessary guideposts. However, recent advances in detector technology have permitted high spatial, temporal and spectral resolution observations with sensitivities sufficient to include a large and hopefully representative sample of late-type stars.

Late-type variable stars are seen to be strongly interacting with their immediate environment by way of net mass outflow. What, then, is the nature of the matter being returned to the interstellar medium? What is the nature of the mass loss mechanism? Why do some objects appear to be almost literally choked in their own dust? The present paper will attempt to provide a brief exploration of the observational data which have an impact on these questions. Since moderate resolution spectrophotometry ($\lambda/\Delta\lambda \sim 50$-$100$) has been obtained for a fairly large (and hopefully représentative) sample of late-type stars (see Merrill and Stein, 1976a,b,c (hereinafter MSI, II, III) for a recent summary), and is most readily available to the author for illustrative purposes, the present discussion will deal primarily with such data. Except where noted, the narrow bandpass ($\lambda/\Delta\lambda \sim 65$) spectra show were obtained at the University of Minnesota-UCSD Mt. Lemmon Infrared Observing Facility.

II. COOL STELLAR PHOTOSPHERES

Observations of cool stellar photospheres provide a window into the interiors of late-type stars and reveal the nature of the material available for mass outflow. Information on opacity sources and energy mechanisms should enable a better understanding of stars undergoing extensive mass loss. The rapid increase in molecular abundances with decreasing effective temperature results in complicated optical spectra which are not yet understood in detail (Fujita, 1970). Molecular dissociative equilibrium calculations (eg. Tsuiji, 1973; Scalo, 1974; Johnson, Beebe and Sneden,

1975) suggest that effective temperature, luminosity class and relative atomic abundances should produce observable differences in the emergent photospheric emission in late-type stars. In particular, the lowering of the oxygen/carbon ratio differentiates red giants into spectral types M, MS, S, SC, and C. Polyatomic species are increasingly important at temperatures below 2800K in comparison to the better studied diatomic species. Molecules provide the dominant opacity source.

The observational picture is summarized by the spectra in Figure 1. (R Lyn and Y Lyn were taken at Mt. Lemmon by B. Jones and S. Willner. The rest are in MSI.) As has been demonstrated by Baldwin, Frogel and Persson (1973) the strengths of the absorption bands due to H_2O at 1.9μ and CO at 2.3μ correlate with spectral type (both deepening with decreasing temperature) and luminosity in normal abundance ("oxygen-rich") stars. Clearly the 2.7μ water absorption band, noticeably present at low resolution by type M3III, dominates the spectra of cool semi-regular and Mira M type variables. Variation of the strength of the infrared steam bands with phase has been confirmed in detail in the 1.2-4.0μ spectra of R Cas (Strecker, Ericson, and Witteborn, 1976 aboard the NASA Kuiper Airborne Observatory - KAO) in agreement with the optical results of Spinrad *et al*.

(1966). Water absorption in the supergiant VX Sgr (Figure 5) is quite pronounced and is clearly seen at 1.9μ in S Per (Strecker et al., 1976).

For stars with O/C near unity, the CO band is incredibly strong (Smyth et al., 1971). Observational coverage of S stars is far from complete (prompting a recent plea for data by Wing and Yorka (1977)). It has been suggested on the basis of near infrared optical spectra that S stars are water deficient compared to M giants of the same temperature (Spinrad et al., 1966). Certainly the MS stars Y Lyn (Figure 1) and RS Cnc (Figure 5) show water absorption, whereas the strong S star R Lyn (Figure 1) shows only saturated CO absorption at 2.3μ.

The spectra of carbon-rich stars are marked by distinctive absorption bands (Figure 1). The 3.07μ band (first noted by Johnson et al., 1968) can become quite deep. Extensive 3μ observations (Noguchi et al., 1977; Fay and Ridgway, 1976; MSI; MSII; MSIII) reinforce the suggestion of Low et al. (1970) that this band is distinctive in cool carbon stars in general. The band is noticeably double in GP Ori, broad and flat bottomed like the 2.3μ CO band in semi-regular variables (UU Aur) and deep and narrow in Mira variables (SS Vir). Preliminary high resolution observations by Ridgway et al.

(1976a,b) suggest the band is composite - including varying amounts of HCN and C_2H_2. C_3 may also be logically present (MSI). The systematic weakening of the 2.3μ CO band in Mira variables has been noted in detail (McCammon, Münch and Neugebauer, 1976; Frogel and Hyland, 1972) and is generally attributed to veiling - possibly by thermal emission in a circumstellar shell. Other bands are also noticeably present at low resolution in carbon Miras. The band at $\lambda > 2.5\mu$ is most probably due to the $\Delta v = -1$ sequence of the C_2 Ballick-Ramsay system (cf. the synthetic C star spectrum of Querci et al., 1974), whell known in carbon stars at shorter wavelengths (MSI; Gilra, 1977). The 3.9μ band may be due to SiC_2 (MSI; Gilra, 1977) since the Merrill-Sanford electronic absorption bands of SiC_2 as well as particulate SiC in emission (Gilra, 1972; Treffers and Cohen, 1974) are already known to be present.

Some important aspects of the 2-4μ spectral absorbance of circumstellar material are summarized in Figure 2 (MSI), where the spectra of an M Mira (o Cet), a C Mira (SS Vir) and a compact infrared source in a molecular cloud (AGL 989) have been divided by appropriate blackbody spectra (2200K, 2150K, and 800K respectively). The enormous strength attainable by water absorption in M stars and the 3.1μ band in carbon stars is quite evident. The observed strength of such bands contrains the degree of veiling present due to circumstellar emission. Such bands are detectable even in the presence of substantial circumstellar thermal dust emission and provide a means of identifying late stars in dense envelopes (MSI, MSII, MSIII). Note in particular that although the carbon star band and the "ice" band (apparently seen primarily in objects embedded in dense molecular clouds; see Merrill, Russell, Soifer 1976) appear at the same wavelength, their spectral shapes are demonstrably different at moderate resolution. It is interesting to note that the long wavelength wings of the steam and "ice" bands are similar.

Observations of the λλ4-8μ spectra of late-type C and M stars from the KAO have been shown the presence of the CO fundamental at 4.6μm (Russell, Soifer, Forrest 1975; Puetter et al., 1977; Goebel et al., 1977). Photospheric blackbody emission is seen in the M supergiants α Ori and μ Cep and the M Mira R Cas near maximum (Russell et al., 1975; Puetter et al., 1977). The 6.2μ steam absorption band is seen in the M Mira R Aql near minimum (Soifer, p.c.) suggesting that the non-detection in R Cas was probably due to the known strong phase dependence in band strength. The smooth spectrum long of the 4.6μ CO fundamental for the C star V Cyg (Puetter *et al.*, 1977) is consistent with veiling by circumstellar emission (known to be large, Forrest (1974)), whereas the possible detection of C_3 absorption long of 5μ in Y CVn (Goebel *et al.*, 1977)(with minimal infrared excess and infrared spectrum like UU Aur in Figure 9) is consistent with detection of the stellar photosphere. The observed weakness of the molecular bands long of 2μ may simply arise as a result of radiative transfer effects in cool stellar photospheres or be due to veiling by chromospheric (Lambert and Snell, 1975), molecular or thermal dust emission.

Ultimately high spectral resolution observations will enable the identification of weaker molecular features in emission and absorption such as SiO in M stars (Hinkle *et al.*, 1976; Cudaback *et al.*, 1971, Wollman *et al.*, 1973) and determine the isotopic abundance ratios in evolved stars (Rank, Geballe and Wollman 1974; Hall *et al.*, 1977; Barnes *et al.*, 1977).

III. CIRCUMSTELLAR DUST ENVELOPES IN LATE-TYPE STARS

A. OVERVIEW

Excess radiation above that expected from a cool stellar photosphere of the temperature indicated by optical spectra is common among late type variable stars. Although it is generally believed that much of this excess is attributable to thermal re-emission by circumstellar dust (Woolf, 1973), plasma processes in the envelope (Gilman 1974) or chromospheric emission (Lambert and Snell 1975) may also contribute substantially to the emergent flux.

Optically thin emission from silicates in M stars (Woolf and Ney, 1969) and silicon carbide in carbon stars (Gilra 1972; Treffers and Cohen 1974) are generally recognized and the spectral shape of the excess emission has been examined in detail at moderate resolution in a large number of cool variable stars (Forrest, Gillett and Stein 1975). The need for a featureless component such as carbon in C stars has also been recognized (Treffers and Cohen 1974, Forrest et al. 1975).

Exploration of the optically peculiar or otherwise unidentified objects in spatially unbiased infrared survey catalogs has pushed the sample of Mira class luminosity variable stars out to 2 kpc and enabled the identification of a wide range in apparent shell optical depth in the circumstellar dust envelopes in late-type stars. Systematic studies of objects in the 2μ Sky Survey (Neugebauer and Leighton, 1969) by Hyland et al. (1972), Strecker and Ney (1974a,b), MSII and others have confirmed numerous clearly identifiable (based on optical and near infrared techniques) late-type stars with dense circumstellar envelopes. For the objects in the rocket-borne AFCRL/AGL Infrared Sky Survey (Walker and Price, 1975; Price and Walker, 1976), although optical techniques are often useful, infrared classification techniques are necessary to identify the stars in the densest envelopes (see Low et al., 1976; Gehrz and Hackwell 1976; Lebofsky et al., 1976; Lebofsky and Kleinmann 1976; Cohen and Kuhi, 1976 and 1977, Allen et al., 1977 and MSIII).

As a persepctive on what follows, the broad bandpass energy distributions of two extreme classes of infrared objects found to be late-type stars are shown subject to arbitrary normalization in Figure 3.[1] Typical cool giants (Figure 3a) emit nearly like blackbodies (solid curves) regardless of O/C ratio. The infrared excess in such stars contains only a fraction of the total flux and photospheric emission dominates the emergent flux. In sharp contrast, stars which resemble the M stars IK (NML) Tau, V1489 (NML) Cyg or the carbon star CW Leo (IRC +10216) (see eg. Strecker and Ney 1974a,b) have their energy distribution over a wide spectral range or resemble cold blackbodies. Thermalized energy re-distribution by

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[1]The energy flux $\lambda F_\lambda = \nu F_\nu$ (W/m^2) is also proportional to photons/unit wavelength. Total blackbody emission is 1.36 times the peak λF_λ and the total 10μ silicate flux for optically thin emission is .34 times the peak λF_λ.

radiative transfer in extensive dust envelopes or other emission processes are clearly present. Such broad band-pass spectra have recently suggested the presence of an additional circumstellar (silicate?) emission band at 33μ in M stars (Hagen, Simon and Dyck 1975) and the possibility of non-silicate emission in S stars (Thomas, Robinson and Hyland 1976).

Figure 4 (MSIII) illustrates the energy distributions of objects from the AGL Survey. (Individual spectra are identified in Table 5 of MSIII.) The objects in Figure 4a exhibit black body-like spectra and are primarily carbon stars while those in Figure 4b show evidence of 9.7μ silicate emission or absorption and are primarily M stars. The objects in Figure 4c form a class of objects embedded in dense circumstellar discs of uncertain evolutionary state and will not be discussed here.

B. SUPERGIANTS

As examples of optically thin shell emission, the λλ 2-14μ spectra of luminous cool supergiants are shown in Figure 5. Characteristically broad 2.3μ CO band absorption is seen in all. Steam absorption is present in the cooler objects (S Per, VX Sgr, RS Cnc). For the hotter stars the spectra appear to be simply due to the superposition of a cool blackbody-like photosphere and optically thin silicate emission closely akin to that seen in emission near the Trapezium stars in Orion (Ney and Allen, 1969; Forrest et al., 1975). This excess is strongest for luminosity class Ia whereas less luminous stars such as CE Tau (M2Ib) show little excess. Woolf (1973) has discussed the onset of silicate emission with spectral and luminosity class. IRC +60370, a highly luminous K star (Humphreys and Ney 1974), has one of the strongest 9.7μ silicate bands known.

The spectra of S Per and VX Sgr (Figure 5) are qualitatively different. The overall trend in their energy distributions roughly parallels a free-free slope. Not only are the optical lines veiled in these stars (Humphreys 1974) but at least in S Per (M3eIa) the 2.3μ CO band appears to be weak in comparison with RW Cyg (M3Ia). The origin of these differences, whether due to radiative transfer in dust or some plasma emission process (Gilman 1974) merits further study. The sharp upturn near 4μm in the spectra of S Per and IRC +60370 (discussed in MSIII) remains unidentified but might be due to SiO emission.

C. M STARS

The observed range in apparent shell optical depth in M stars is summarized in Figure 6. (AGL 2205 is from

Forrest et al., 1977. The spectra not present in MSI, MSII, or MSIII are from the author's unpublished data.) The combined $CO-H_2O$ absorption bands appear in all the λλ 2-4μ spectra, becoming increasingly veiled by circumstellar thermal dust emission with decreasing apparent 2-4μ color temperature. The named stars are all unambiguously identified as M type variable stars on the basis of optical or near infrared classification techniques. The AGL sources are identified as M stars due to the presence of the $CO-H_2O$ band absorption.

The 9.7μ silicate band increases from moderate (o Cet) to strong emission in the Mira TX Cam (or the supergiant VX Sgr of Figure 5) and starts into possible self absorption in IK (NML) Tau. As the apparent 2-4μ color temperature decreases, the 9.7μ band undergoes distinct self-absorption in the band center while still in net emission in the wings in NV Aur (IRC +50137) and V1489 (NML) Cyg (also in IRC -10529 and WX Psc (IRC +10011) (MSII) not shown here). In AGL 2885 and AGL 2290 the 9.7μ band is deeply into net absorption. Finally in AGL 2205 (OH 26.5 + 0.6) the 9.7μ band is very deep and the apparent 2-4μ color temperature a chilly 375K. The flux from all these objects varies with Mira class time scales. All but AGL 2885 are recognized OH maser radio emitters.

The 2-40μ spectrum of AGL 2205 is shown in Figure 7 (Forrest et al., 1977). In a situation analogous to that of the 9.7μ silicate band in NV Aur the 18μ silicate band appears near the point of net absorption at the band center. The total flux of this star varies on Mira time scales. The color temperature decreases and the depth of the 9.7μ band absorption increases near minimum suggesting the overall cooling of dust in the envelope in response to variations in luminosity of the central star. As an OH Tye II (Andersson et al., 1974) maser undergoing cyclic bolometric luminosity changes, and possessing a silicate dust envelope through which remnant CO-H_2O absorption can still be seen, AGL 2205 is almost certainly an M type variable star undergoing extensive mass loss. The 1800K curve results from a simple de-reddening of the observed flux by the observed 2-4μ extinction curve determined towards VI Cyg #12 (Gillett et al. 1976) and is plotted to illustrate the residual presence of the CO-H_2O band. The overall energy distribution is predictably not well fit by a blackbody. Recent infrared surveys of OH sources by Schultz, Kreysa and Sherwood (1976) and Evans and Beckwith (1977) suggest such OH/IR stars in dense dust envelopes are not rare. Other AGL candidates include AGL 290, 1822, 1992, 2019, 2086, 2174, and 2188 to name but a few (see, eg., Lebofsky et al., 1976; Allen et al., 1977). Such objects are returning massive amounts of silicate-rich dust, CO, SiO, OH and H_2O to the interstellar medium.

D. LABORATORY SPECTRA OF SILICATES

Extensive laboratory investigations of the infrared properties of mineral silicates have gradually led to a better understanding of the circumstellar silicate band (see, eg. Dorschner 1971; Perry et al., 1972; Pollack, Toon, and Thare 1973; Knacke and Thompson 1973; Day 1974, 1976; Day et al., 1974; Steyer 1974; Steyer, Day, and Huffman 1974; Hunt and Salisbury 1974, 1976; Zaikowski and Knache 1975; Zailkowski, Knacke and Porco 1975; Dorschner, Gürtler, and Friedemann 1976; Penman 1976a). A generally amorphous, randomized low order crystal structure seems to come closest to duplicating the 9.7μ absorption band. Recently Rose (1977a) has attempted to duplicate the infrared emission spectra of comets by direct laboratory measurements of grain emission. Typical results for ~600K grains are shown in Figure 8. The 9.7μ emission band seen in the Orion Trapezium region shown here for comparison (Figure 8) reasonably matches the observed excess emission in M stars (Forrest et al., 1975). Excellent fits to the observed 9.7μ absorption in a variety of infrared sources are possible for an assumed 250K Trapezium emission temperature (Gillett, Forrest, et al., 1975). Assuming such an isothermal cloud as a first approximation (an attempt to allow for temperature and density gradients in the Trapezium would yield somewhat different results (Bedijn, 1977)), the 9.7μ band translates as indicated from grains at 250K to 350K and 600K. The 0-2μ sized Montmorillonite emission is a very good match. Zaikowski et al. (1975) have previously commented on the close match of such phyllosilicates to observed absorption spectra in a variety of galactic sources. Rose (1977b) concludes that several reasonable mixtures of high and low temperature condensates or amorphous high temperature condensates provide reasonable fit to the observed comet spectra. Such ensembles of varied silicate grain size, shape, and composition also fit the 9.7μ emission band (see also Forrest 1974) as can be inferred from Figure 8.

E. C STARS

The observed range in shell optical depth in carbon stars is shown in Figure 9. (AGL 3099 was taken at KPNO by Gehrz (p.c.), the rest are from MSI, MSII, MSIII.) Cool carbon stars such as UU Aur have black body like continua. Strong SiC emission is seen near 11.2μ in UU Aur and the Mira R Lep. The 2-4μ color temperature reddens as the energy distribution gradually thermalizes to a cold $\lesssim$600K apparent blackbody temperature. The 3μ absorption bands are clearly visible. Unlike the M stars, no new absorption bands appear with increasing shell optical depth. SiC is clearly seen in all cases shown (AGL 865 data are too noisy to tell). The primary constituent of the dust in carbon-rich envelopes is relatively featureless (Forrest et al. 1975) and is generally considered to be carbon (implying an emissity of $1/\lambda^2$ for small grains).

The properties of rich molecular envelopes of stars like CW Leo (IRC +10216) have been recently summarized by Morris (1975). High resolution 2μ spectroscopy of CW Leo (Hall et al. 1977) has detected CO in the shell and along with data at 4.7μ Rank et al. (1974) and radio data are beginning to establish isotope ratios in the evolved material. A mass of $10^{-2} M_\odot$ is suggested for the molecular cloud (Hall et al. 1977). Again, such dense expanding CO clouds are not rare (Zuckerman et al. 1977). A significant fraction of the AGL Survey sources are such carbon stars. Such carbon stars are returning condensed carbon and SiC, gaseous CO, and other metallic molecules to the interstellar medium.

IV. INFRARED EMISSION DURING LATE EVOLUTIONARY PHASES

A. NOVA (NQ) VULPECULA 1976

The 2-8μm spectrum during an early stage in the development of Nova (NQ) Vul 1976 is shown in Figure 10. the λλ 2-4μ (from Mt. Lemmon, 31 Oct. 1976) and the λλ 4-8μ (Soifer, p.c. from the KAO, 5 Nov. 1976) spectra have been matched according to the appropriate overlapping broad bandpass data. During this stage the overall energy distribution showed variable, approximately free-free infrared emission and strong visual flux (Ney and Hatfield, 1977; Neugebauer, Gehrz, Soifer, p.c.). Numerous hydrogen lines (probably blended at this resolution (λ/Δλ ~ 65) with helium lines) are seen, including the Pfund series limit. The line at 3.37μ remains unidentified. As was noted in Nova FH Ser 1970 (Geisel,

Kleinmann and Low, 1970) the [4.9μ] band was clearly stronger than could be accounted for by hydrogen lines. The λλ 4-8μ spectrum communicated by Soifer (p.c.) clearly exhibits a strong, broad emission feature from the atmospheric cut-on at 4.5μm to 5.4μ and beyond. Groundbased 5μ spectra by Gehrz (p.c.) confirm the band emission. Overlapping broad bandpass observations on the two days suggest the spectra are properly normalized to each other to within about ±15%. By comparison with Humphreys α(H 6-5) the hydrogen lines are a minor peturbation on.the band.

J. Black (p.c.) has suggested C_3 emission as being responsible for this band. The band disappeared in the broad bandpass data just prior to the onset of grain formation near day 64 (Ney, 1977; Ney and Hatfield 1977). Later spectra (Gehrz, p.c.) show a cool blackbody and are consistent with subsequent broadband data which indicate approximately 900-1000K blackbody emission. It is tempting to suggest that a super-saturated C_3 vapor rapidly concensed into carbon.

B. HM SAGITTAE

The remarkable emission-line object HM Sagittae, first reported by Dokuchaera (1976) as an object which had brightened over 5 magnitudes in two years, has been suggested as a planetary nebula in the early stages of formation akin to V1016 Cyg (Stover and Sivertsen, 1977; Ciatti et al. 1977). The broad bandpass energy distribution during June 1977 is shown in Figure 11 (Davidson, Humphreys, and Merrill, 1977) along with that of V1016 Cyg and CRL/AGL 1274, a possibly related object which is still visually faint (Allen et al. 1977 and Cohen and Kuhi 1977). The 9.7μ silicate band (confirmed by selected narrow bandpass points) is apparently seen in emission above a 100K blackbody-like emission. It is perhaps significant that the nova NQ Vul and HM Sge differ in the absence and the presence of silicates respectively but are alike in the apparent color temperature of the bulk of the observed emission. Apparently temperatures near 1000K permit substantial grain condensation.

C. UNIDENTIFIED BAND EMISSION

Having hopefully impressed everyone with our collective wisdom concerning the state of the material returning to the interstellar medium through mass loss from late-type stars, it is now necessary to impress upon everyone the profound depths of our collective ignorance. The concept of assorted simple molecules coexisting with refractory materials such as silicates, graphite, and silicon carbide (or possibly even polysaccharides as has been suggested by Hoyle and Wickramasinghe, 1977) is quite appealing. However we are unable to account for what is gradually becoming known as one of the more ubiquitous emission processes observed in the infrared!

Infrared spectra of the nuclei of the galaxies M82 and NGC 253, assorted planetary nebulae and galactic HII regions and certain peculiar stars are marked by strong, unidentified band structure which often dominates the observed energy flux. (cf. Gillett et al. 1973; Gillett, Kleinmann et al. 1975; Grasdalen and Joyce 1976;

Merrill, Soifer, Russell 1975; Cohen et al. 1975; MSIII; Kleinmann et al. 1977; Russell, Soifer, Merrill 1977). New sources are continually being confirmed, representing apparently diverse evolutionary states, temperatures, densities and excitation conditions. Yet, as is true for the 9.7μ band, the band centroids and spectral shapes appear to be remarkably constant.

This challenging state of affairs is summarized in Figure 12 where the 2-13μ spectra of representative objects are shown. (Data shown originated as follows in the 2-4μ, 4-8μ and 8-13μ regions: HD 44179 (Russell, Soifer, Merrill 1977; Russell et al. 1977b; Cohen et al. 1975), NGC 7027 (Merrill, Soifer, Russell 1975; Russell et al. 1977a; Russell et al. 1977a), and AGL 3053 (Joyce (pc. at KPNO), Soifer (p.c. from the KAO); Merrill, (unpublished).) The nebula NGC 7027 has always been a challenge. The observed spectrum is nearly orthogonal to the anticipated free-free continuum. Extensive far infrared (Telesco and Harper 1977) and CO radio emission (Mufson, Lyon and Marionni 1975) are also present. HD 44179 (Cohen et al. 1975) is an apparent low excitation nebular binary system imbedded in a dense circumstellar disc. AGL 3053 is a region of extended infrared emission (Joyce et al. 1977) near the compact radio source surveyed by Israel, Habing and de Jong (1973) in Sharpless 159.

Excluding from this discussion the assorted atomic forbidden and permitted lines and molecular hydrogen lines seen in NGC 7027, I draw your attention to bands at 3.3μ (with shoulder or separate band at 3.4μ), 6.2μ, 7.8μ, 8.6μ, and 11.2μ. Although the original suggestion (Gillett _et al_. 1973) that the 11.2μ feature might be due to mineral carbonates has been supported by laboratory investigations (Bregman and Rank 1975; Penman 1976b) the absence of the strong ν_3 fundamental near 7μm is hard to explain and the association of the 8.6μ feature with mineral sulfates (Cohen _et al_. 1975) is similarily difficult to support. At resolution $\lambda/\Delta\lambda \gtrsim 200$ both the 8.6μ and 11.3μ features remain continuous (Bregman 1977, Bregman and Rank 1975). The 3.3μ feature discussed at length by Russell, Soifer and Merrill (1977) and Gradalen and Joyce (1976) remains continuous at higher resolution ($\lambda/\Delta\lambda$ ~ 300 and possibly even at 3000). This lack of structure, along with the observed uniformnity of band shape and centroid for an apparently wide range of physical conditions, argue against identification with a molecular band (such as CH/CH^+ suggested by Grasdalen and Joyce (1976)). Observations of NGC 7027 and HD 44179 from the NASA KAO (Russell, Soifer, and Willner 1977a,b) have added the bands at 6.2μ and 7.8μ to the list.

The features remain tantalizingly unidentified. Although the present state of affairs is hardly comparable, one cannot help being reminded of the situation that existed not so very long ago with the discovery of "nebulium" in planetary nebulae. Any successful description of the observed phenomona must account for all the data - the bands which are not present as well as those which are present.

V. SUMMARY

Table I summarizes the principal well established infrared signatures currently recognized at moderate spectral resolution ($\lambda/\Delta\lambda \sim 50$-100). Approximate centroids, widths (for emission), whether seen in absorption or emission, possible cause, and example sources are listed. Bands seen only at high resolution, as for example the 4μ SiO bands (Hinkle et al. 1977) are not included here. Even at such moderate resolution the number of observed bands has continued to grow. Besides providing information on the materials in the circumstellar environment of late-type stars, such band structure often facilitates the meaningful classification of otherwise unidentifiable infrared sources (MSIII). Large numbers of late-type stars are known to be undergoing extensive mass-loss, irrespective of photospheric chemistry as determined by the products of nucleosynthesis. There is as yet no reason to assume that the upper limit to shell optical depth and inferred mass-loss has yet been observed. It would appear that mass-loss occurs throughout the later phases of stellar evolution. Periods of high mass-loss, marked by dense circumstellar dust envelopes, may well be endemic as an evolved star adjusts to the changing conditions deep within its interior.

The observational consequences of the recycled material are distinctly different both in the photosphere and in the circumstellar dust envelope as determined by impact of the physical state and the evolutionary history of the parent star on the chemistry in the shell. While the composition of much of this matter is identifiable with at least some degree of confidence, the identity of a significant fraction of the material is presently unclear. An as yet unidentified material of unknown origin provides the dominant infrared emission mechanism in a variety of infrared sources.

Much can be learned about the mass-loss phenomenon in late-type stars on the basis of moderate resolution infrared spectrophotometry. However, implementation of new technology will enable high spectral resolution infrared observations to be used in conjunction with improved radio data to identify molecular bands, establish isotopic ratios, and monitor shell dynamics. Lunar occulation (Toombs et al. 1972) and spatial interferometry (McCarthy, Low and Howell 1977; Sutton et al. 1976) can determine the angular diameters of circumstellar dust envelopes. Detailed radiative transfer calculations and kinematic shell models (such as Bedijn 1977; Olnon 1977; Finn and Simon 1977; Apruzese 1976; Goldreich and Scoville 1976; Jones and Merrill 1976; Taam and Schwartz 1976; Schmidt-Burgk and Scholz 1976; Dyck and Simon 1975; Kwok 1975; Salpeter 1974) will be required to fully realize the physical state of these dusty circumstellar envelopes. We have truely only just begun.

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Figure 1 - Relative λλ 2-4μ spectrophotometry of late-type stars illustrating the variation in photospheric molecular band absorptions with temperature, luminosity, oxygen/carbon ratio and variability class. Shown (top to bottom) are: α Boo, δ Vir, RZ Air, RX Boo, o Cet, Y Lyn, R Lyn, GP Ori, UU Aur and SS Vir, identified by spectral type and variability class.

Figure 2 - Observed λλ 2-4μ absorptance in circumstellar envelopes. Spectra (top to bottom) have been divided by appropriate blackbodies to better define band structure: o Cet (2200K) an M star; SS Vir (200K), a C star; and AGL 989 (800K) a compact infrared source in a molecular cloud with the "interstellar ice" band.

Figure 3 - Relative energy flux of late-type stars with minimal infrared excess consistent with photospheric emission (Panel a) and with large infrared excess indicative of thermalized emission from an extensive dusty circumstellar envelope (Panel b). Stars shown (top to bottom) in Panel a: α Boo (K2III), α Ori (M2Ia), UU Aur (C5,4), R Lep

(C7,6e), o Cet (gM7e), 10,000K and 2400K blackbodies; Panel b: CW Leo (open circles), IK Tau (filled circles) and V1489 Cyg (squares), 10,000K and 600K blackbodies.

Figure 4 - Relative energy flux of representative objects in the AGL Infrared Sky Survey from MSIII (individual objects are identified in Table I of MSIII.) In Panel a are primarily C stars; in Panel b, primarily M stars (or at objects with O/C normal); and in Panel C, objects of uncertain evolutionary state surrounded by dense circumstellar disc-like envelopes.

Figure 5 - Relative λλ 2-13μ spectrophotometry of representative luminous cool stars (M and K supergiants). A 3300K blackbody and a free-free slope are included for comparison.

Figure 6 - Relative λλ 2-13μ spectrophotometry of M stars illustrating the observed range in total optical depth in dusty circumstellar envelopes.

Figure 7 - Observed λλ 2-40μ spectrum of AGL 2205 (OH26.5 + 0.6) from Forrest *et al.* (1977). A 375K blackbody curve and the 2-4μ spectrum de-reddened using the extinction law observed towards VI Cyg #12 are also shown.

Figure 8 - Observed relative emission spectra for small (0-2μ) grains at ~600K from the laboratory measurements of Rose (1977) for Lunar soil 15531 (L), a melted anorthite (A), Montmorillonite (M), Columbia River Basalt (B), Dunite (D), and amorphous silicate (S). The observed emission from the Orion Trapezium is shown (Forrest et al. 1975) renormalized from assumed 250K grains to 350K and 600K grains for comparison.

Figure 9 - Relative λλ 2-13μ spectrophotometry of C stars illustrating the observed range in total optical depth in circumstellar dusty envelopes.

Figure 10 - Spectrophotometry of Nova (NQ) Vulpecula 1976 during the free-free emission phase, taken 31 Oct. 1976 (2-4μ) and 5 Nov. 1976 (4-8μ). Overlapping broad bandpass data agree to ±15%. Positions of hydrogen lines are indicated. Energy flux at 3.0μ is 3.0×10^{-15} W/cm^2.

Figure 11 - Energy flux from HM Sge during June 1977 together with possibly similar objects from Davidson, Humphreys, and Merrill (1977).

Figure 12 - Relative λλ 2-13μ spectrophotometry of representative infrared sources with unidentified emission features at 3.3μ/3.4μ, 6.2μ, 7.9μ, 8.6μ and 11.2μ. Points with broad horizontal bars are broad bandpass observations

TABLE I

OBSERVED INFRARED BANDS

AT MODERATE SPECTRAL RESOLUTION

($\lambda/\Delta\lambda$ ~ 50-100)

BAND CENTER (μm)	BAND WIDTH (μm)	abs	em	CAUSE	WHERE SEEN
1.4,1.9,2.7, 6.2		X		g:H_2O	M stars
1.6,2.3,4.7		X		g:CO	cool stars
~2.6		X		g:C_2?	carbon stars
3.07		X		g:C_3,C_2H_2,HCN,?	carbon stars
3.07		X		"ices"	molecular clouds
3.9		X		g: SiC_2?,C_2?	carbon stars
~1.9-2.5	lines		X	g:H_2	nebula
3.28	~0.05		X	?	nebulae, pec. stars
3.4	0.2		X	?	nebulae, pec. stars
~4.9	~0.8	X?	X	g:C_3?	carbon stars, Nova Vul 19
6.2	0.3		X	?	nebulae, pec. stars
~7.7	0.8		X	?	nebulae, pec. stars
8.6	0.3		X	?	nebulae, pec. stars
9.7 ,18	~3+	X	X	silicates	oxygen rich stars, ISM
~11.2	~1.7		X	silicon carbide	carbon rich stars
11.2	0.4			?	nebulae, pec. stars
12.8	~0.3		X	?	nebulae

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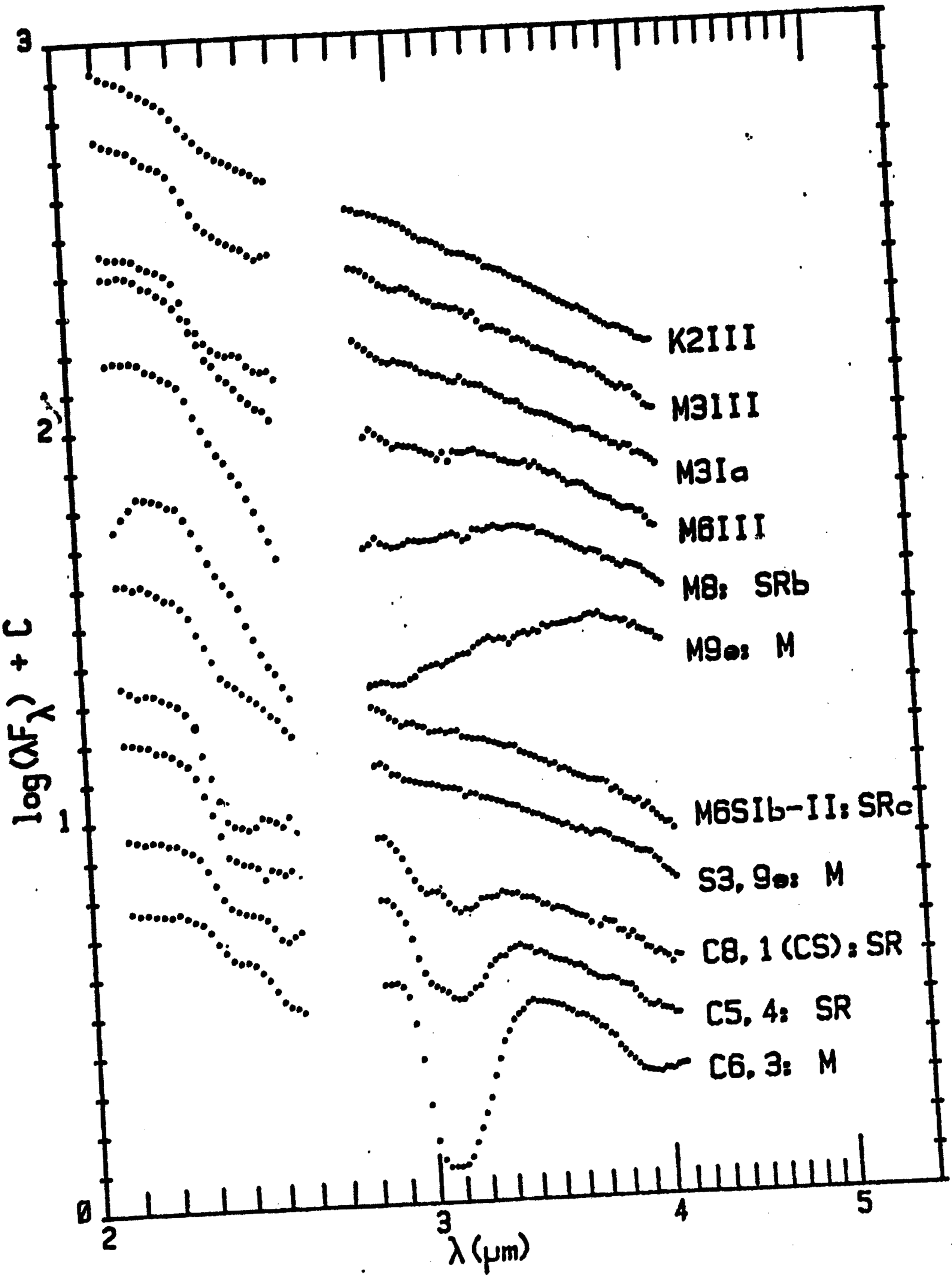
FIGURE 1



3
2
1
0
log(λF$_λ$) + C
2
3
4
5
λ (μm)
K2III
M3III
M3Ia
M6III
M8: SRb
M9e: M
M6SIb-II: SRc
S3, 9e: M
C8, 1 (CS): SR
C5, 4: SR
C6, 3: M

FIGURE 2

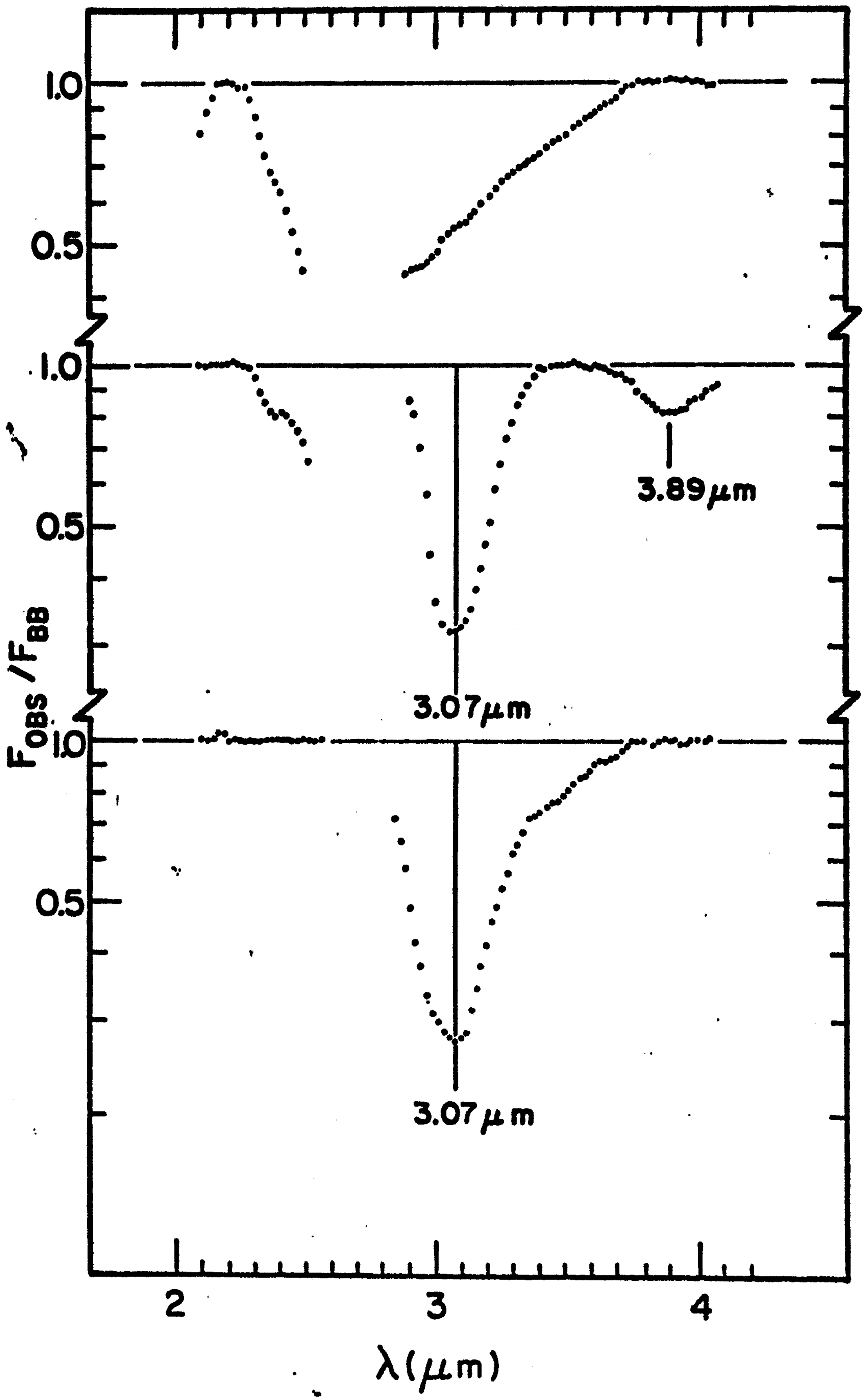


FIGURE 3

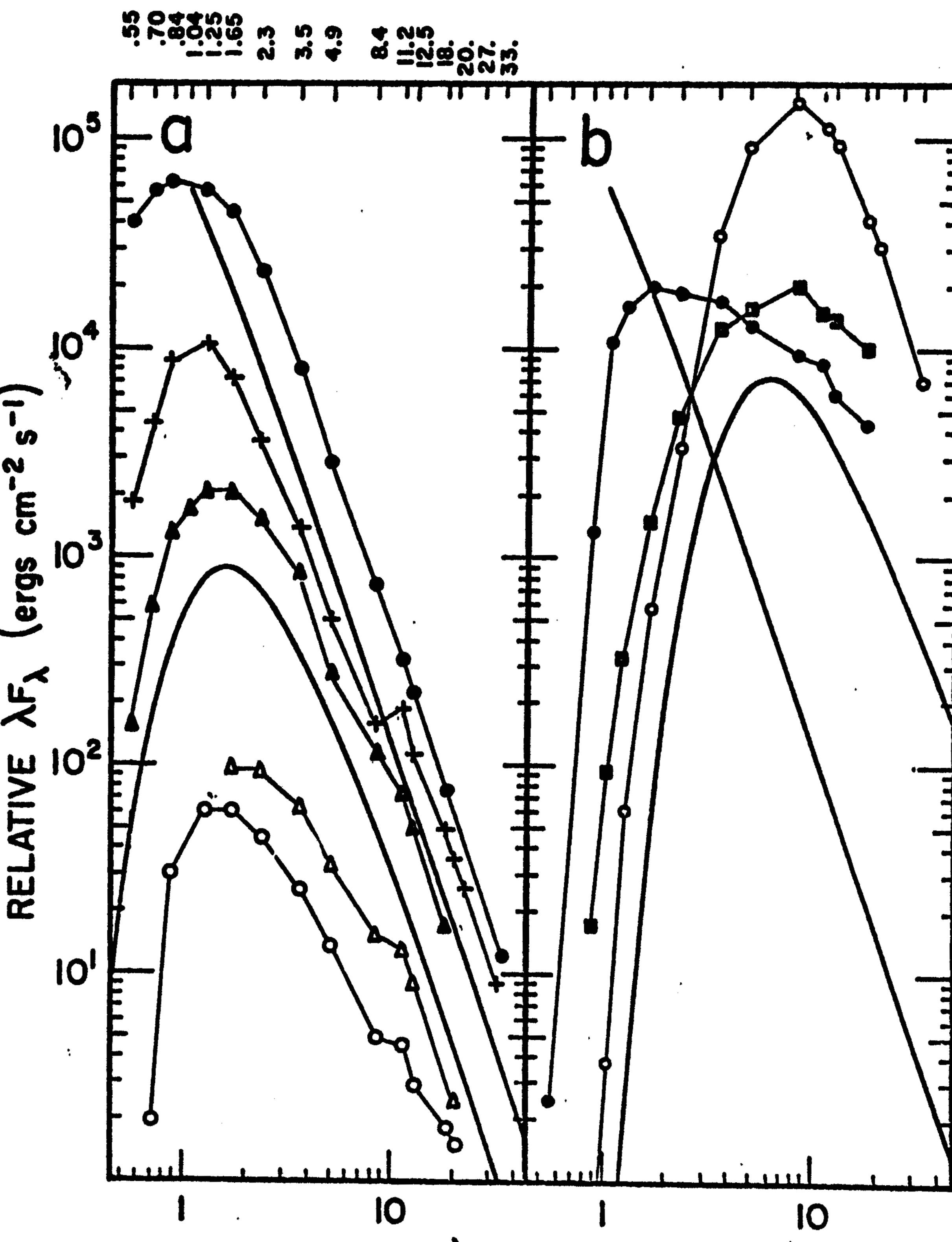
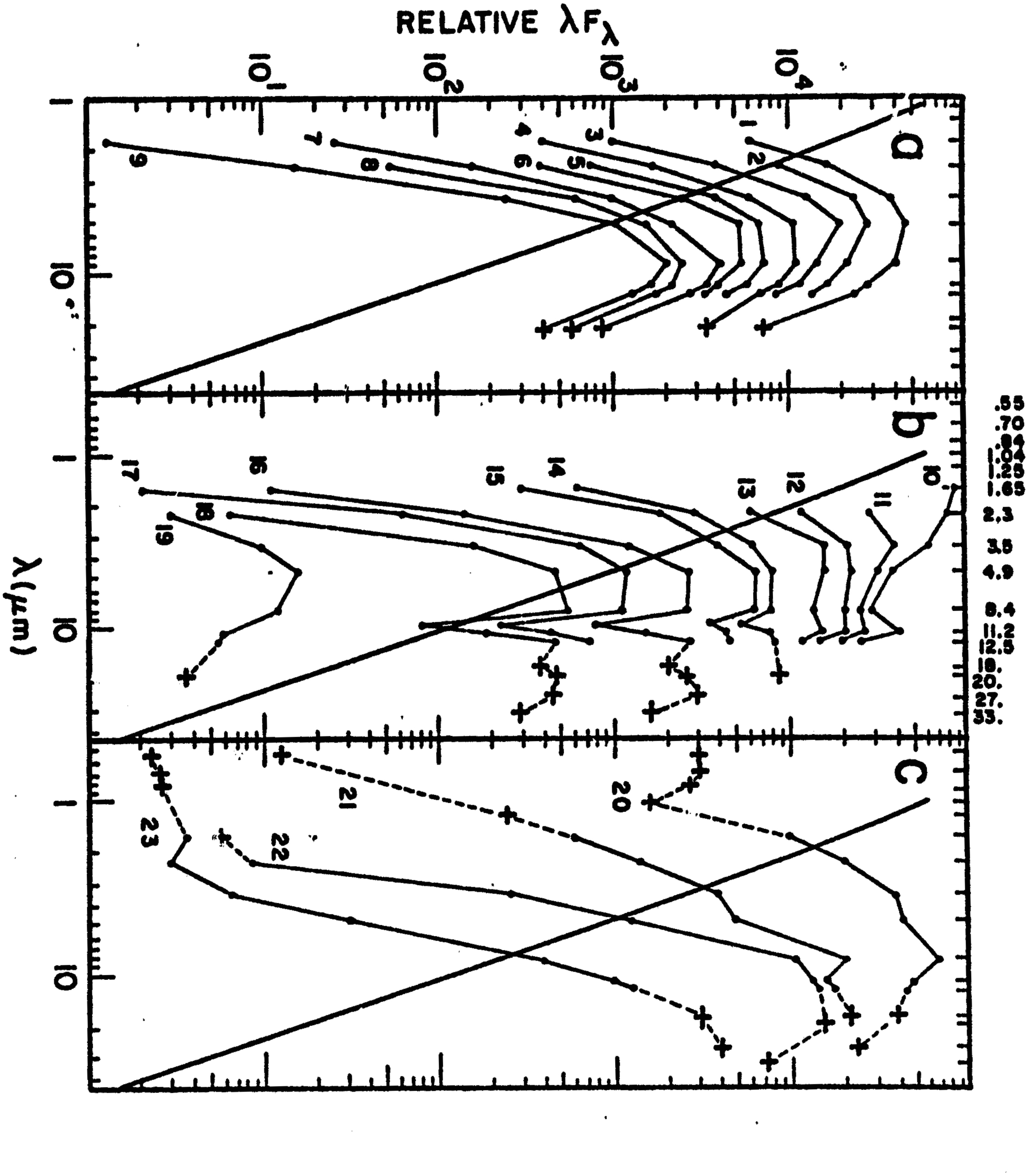
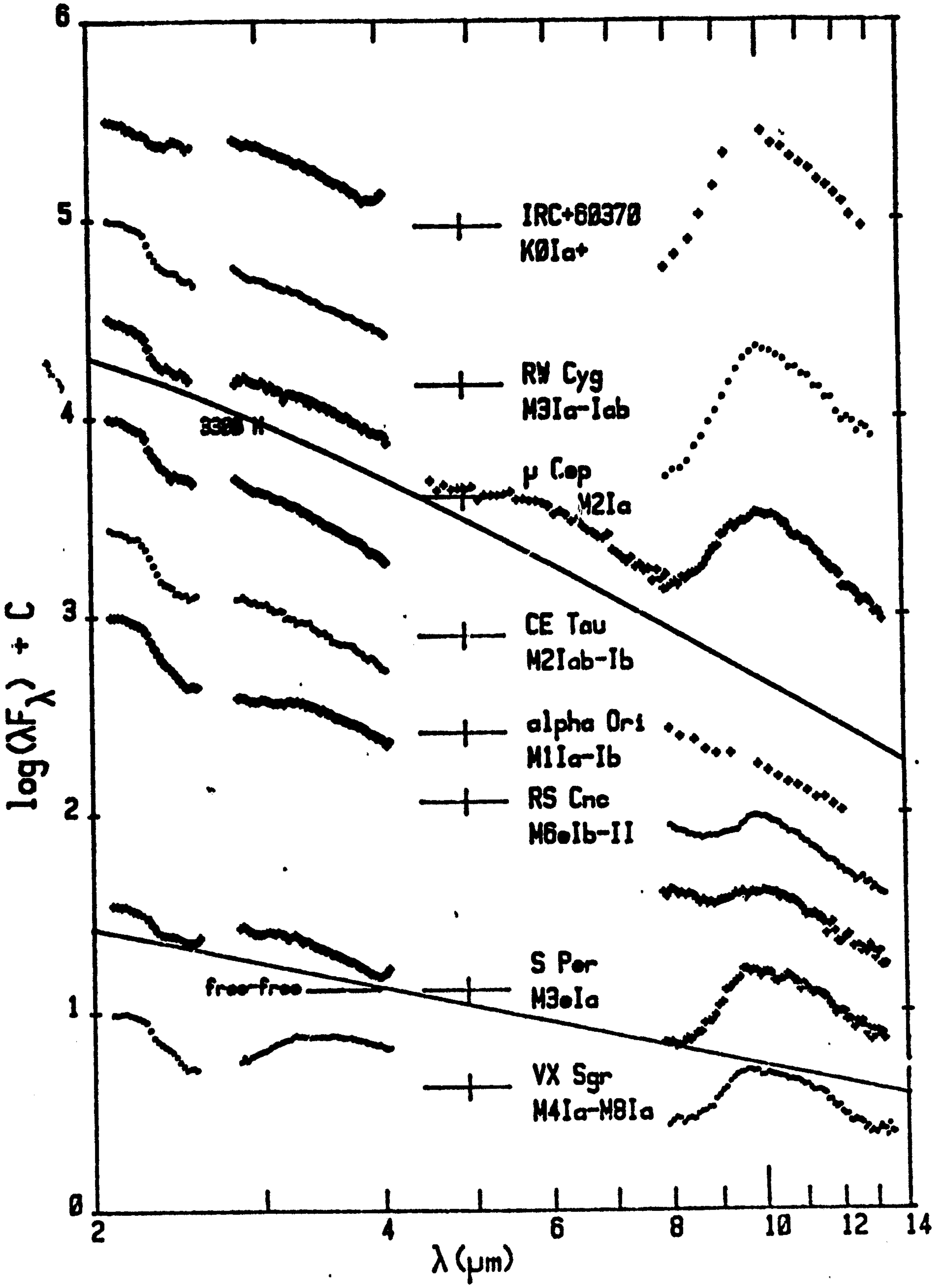

.55
.70
.84
1.04
1.25
1.65
2.3
3.5
4.9
8.4
11.2
12.5
18.
20.
27.
33.
a
b
10^5
10^4
10^3
10^2
10^1
RELATIVE λF_λ (ergs cm^{-2} s^{-1})
1
10
1
10
λ (μm)

FIGURE 4



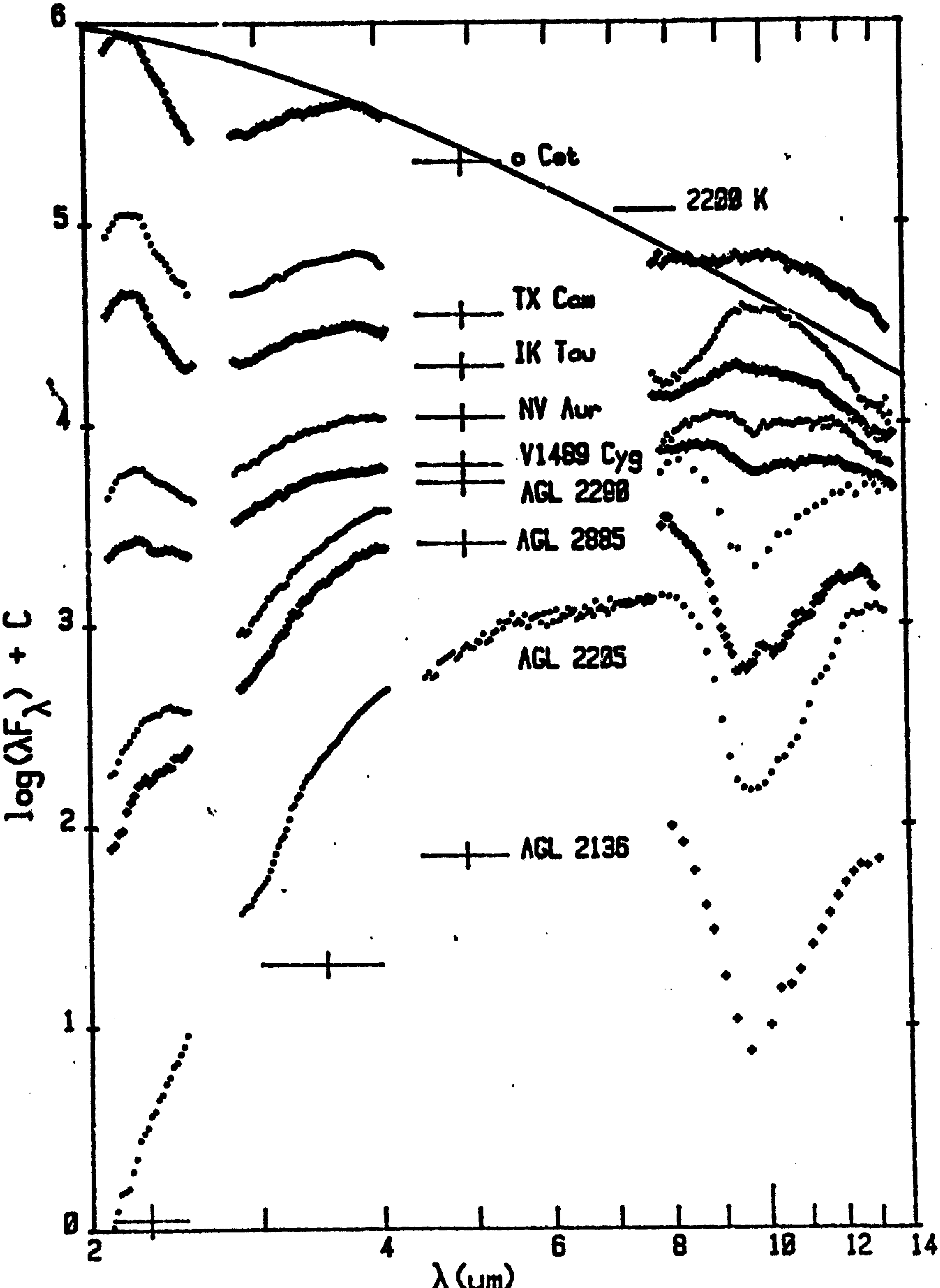
RELATIVE λF_λ
λ(μm)
a
b
c
.55
.70
.84
1.04
1.25
1.65
2.3
3.5
4.9
8.4
11.2
12.5
18.
20.
27.
33.

FIGURE 5

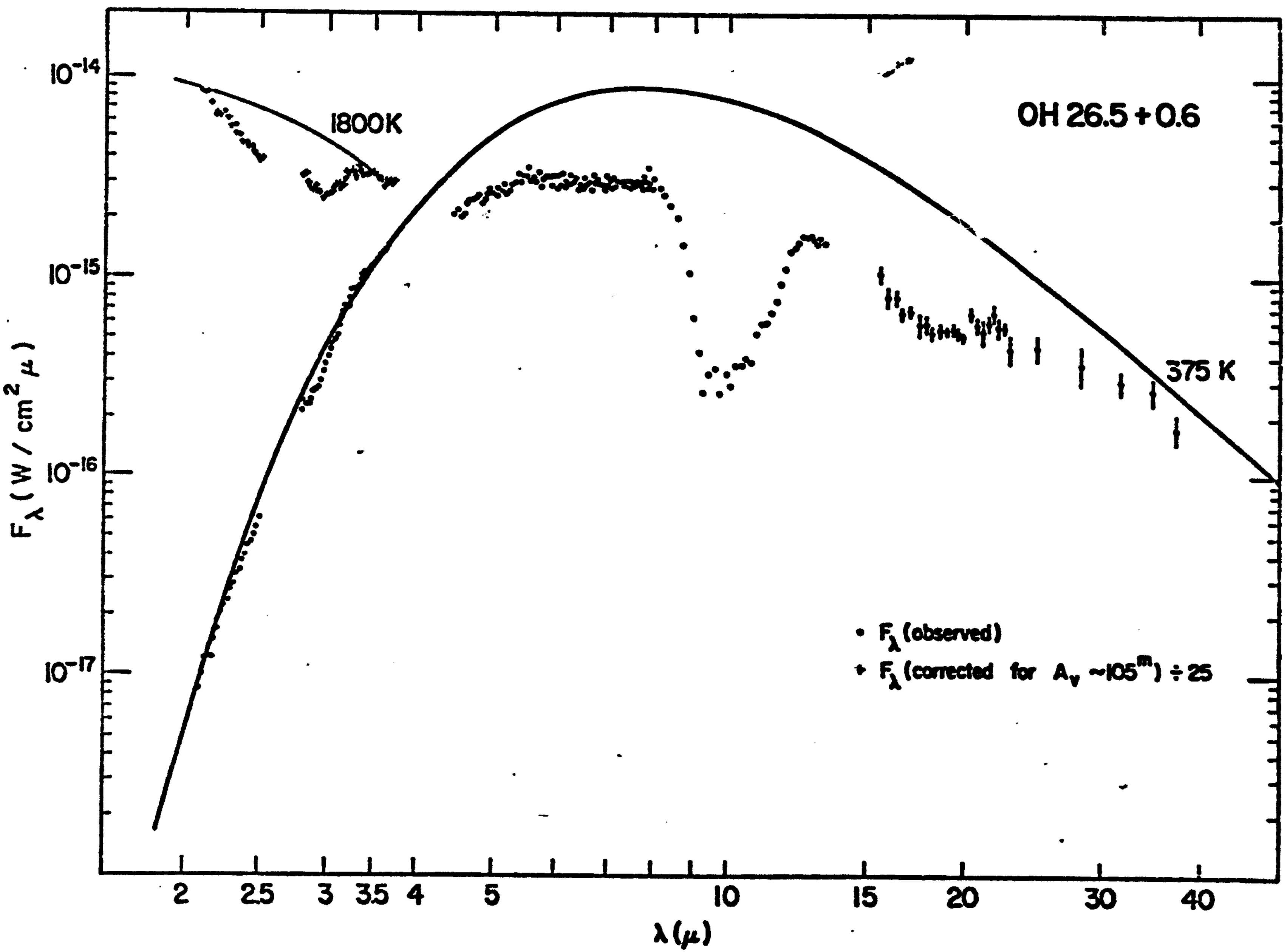


IRC+60370
K0Ia+
RW Cyg
M3Ia-Iab
3300 K
μ Cep
M2Ia
CE Tau
M2Iab-Ib
alpha Ori
M1Ia-Ib
RS Cnc
M6eIb-II
free-free
S Per
M3eIa
VX Sgr
M4Ia-M8Ia
log(λF_λ) + C
λ (μm)
0
1
2
3
4
5
6
2
4
6
8
10
12
14

FIGURE 6



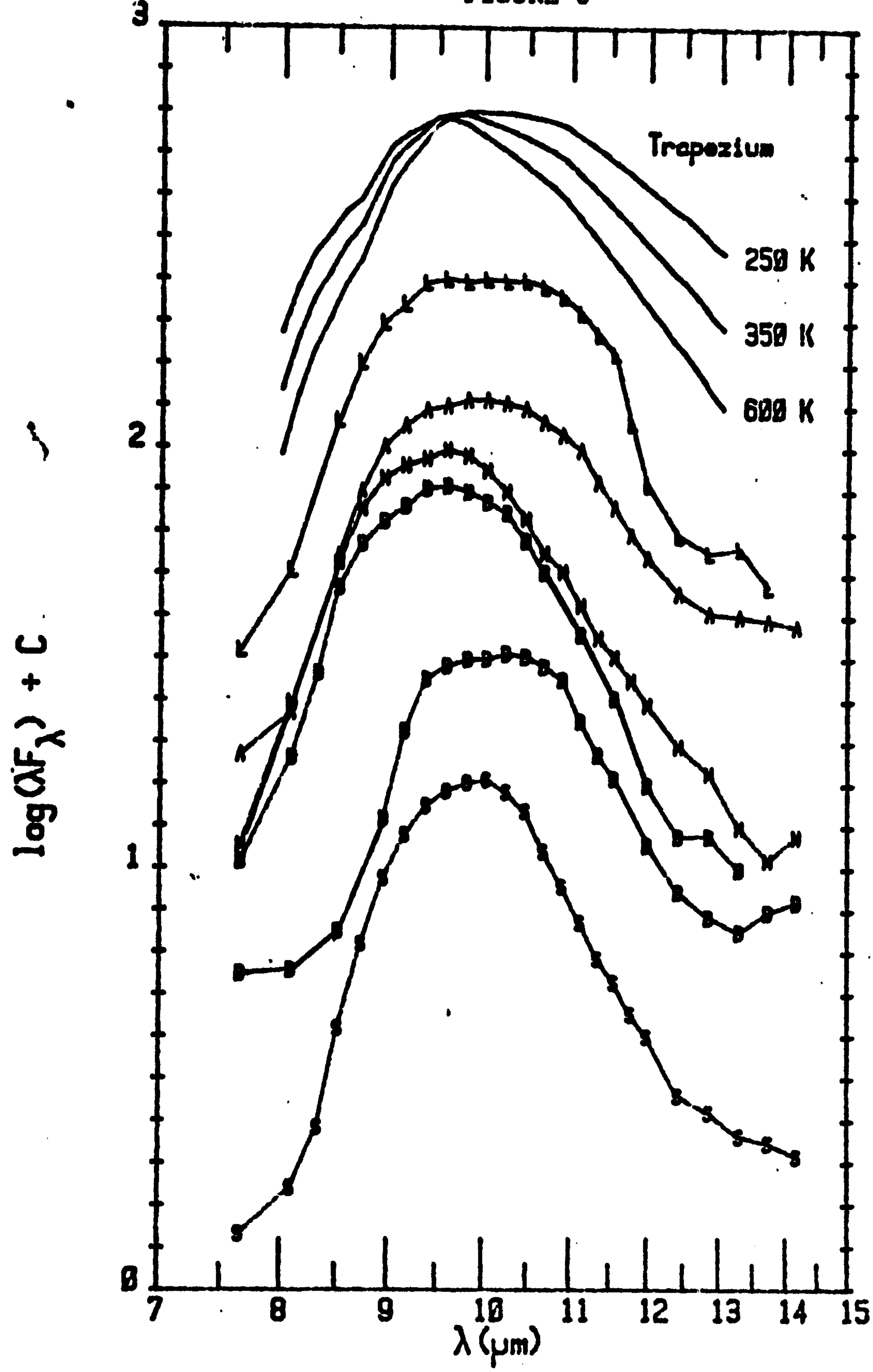
o Cet
2200 K
TX Cam
IK Tau
NV Aur
V1489 Cyg
AGL 2290
AGL 2885
AGL 2205
AGL 2136
log(λF$_\lambda$) + C
λ(μm)
0
1
2
3
4
5
6
2
4
6
8
10
12
14



10^{-14}
10^{-15}
10^{-16}
10^{-17}
F_λ (W / cm^2 μ)
1800K
OH 26.5 + 0.6
375 K
• F_λ (observed)
+ F_λ (corrected for A_V ~105^m) ÷ 25
2
2.5
3
3.5
4
5
10
15
20
30
40
$\lambda(\mu)$

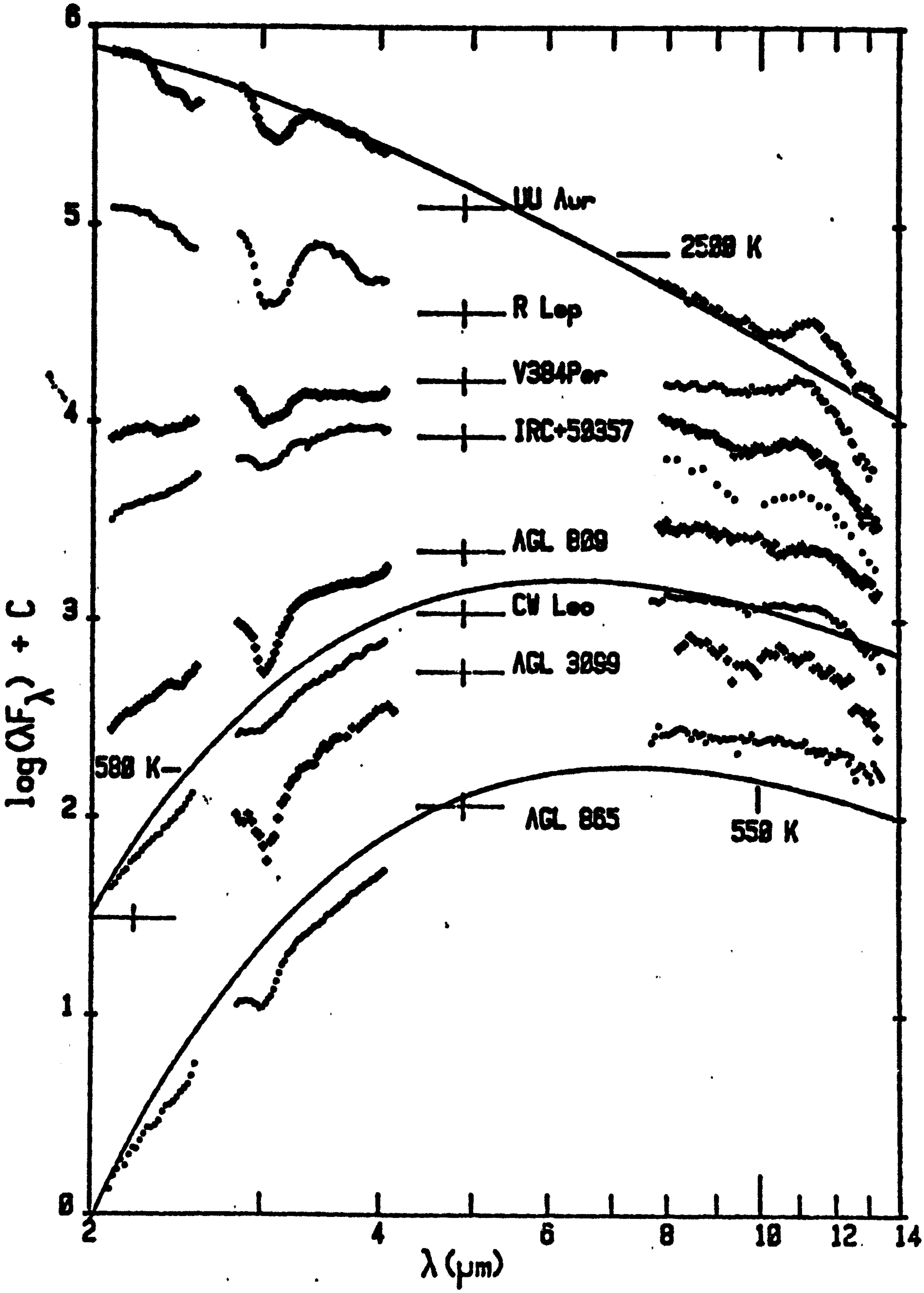
FIGURE 7

FIGURE 8



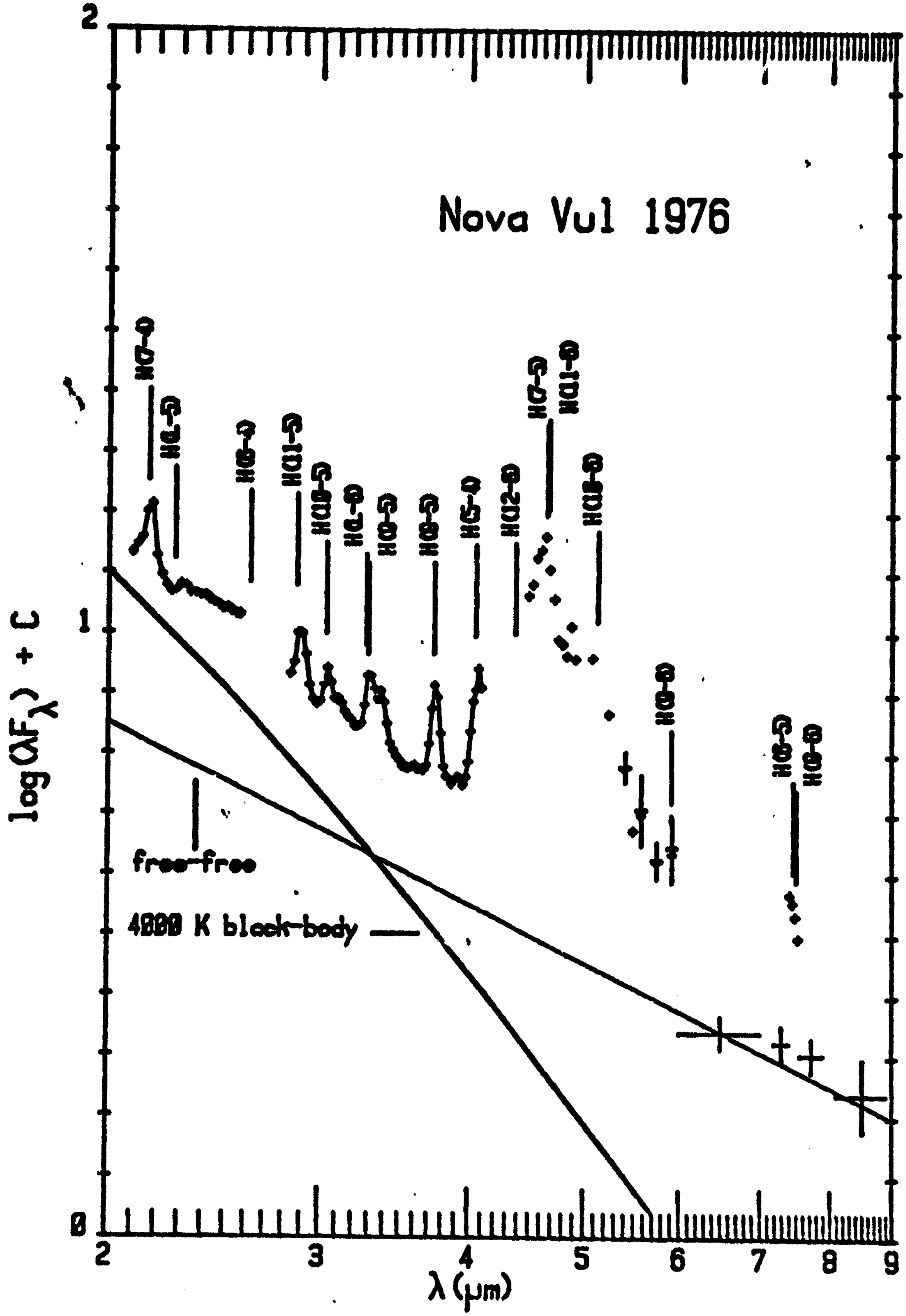
Trapezium
250 K
350 K
600 K
log(λF_λ) + C
0
1
2
3
7
8
9
10
11
12
13
14
15
λ (μm)

FIGURE 9



UU Aur
2500 K
R Lep
V384Per
IRC+50357
AGL 809
CW Leo
AGL 3099
500 K
AGL 865
550 K
log(λF$_λ$) + C
λ(μm)
0
1
2
3
4
5
6
2
4
6
8
10
12
14

FIGURE 10


Nova Vul 1976
H(7-4)
H(11-5)
H(10-5)
H(5-4)
H(12-6)
H(7-5)
H(11-6)
H(10-6)
free-free
4000 K black-body
log(λF$_\lambda$) + C
λ (μm)
2
1
0
2
3
4
5
6
7
8
9

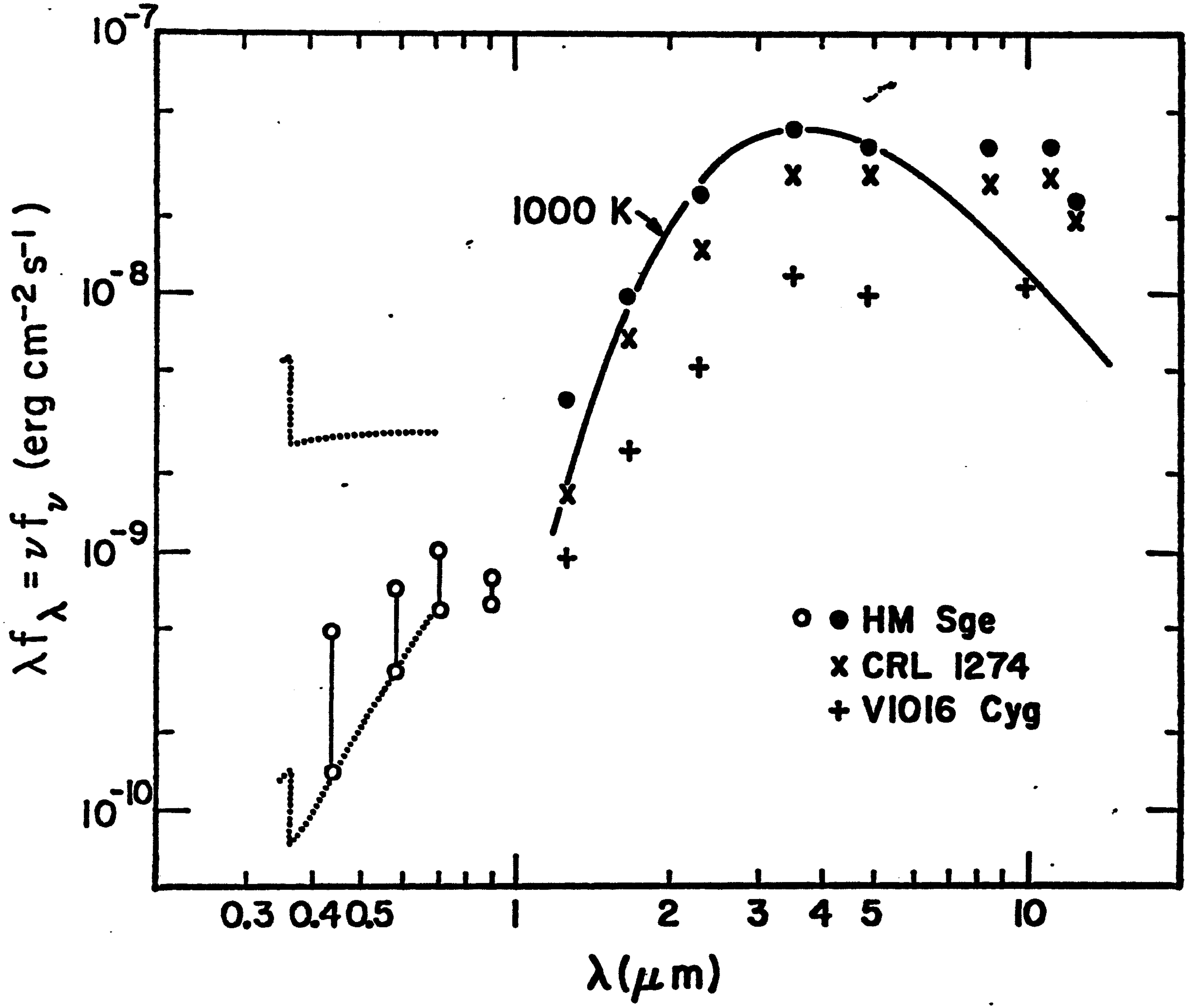
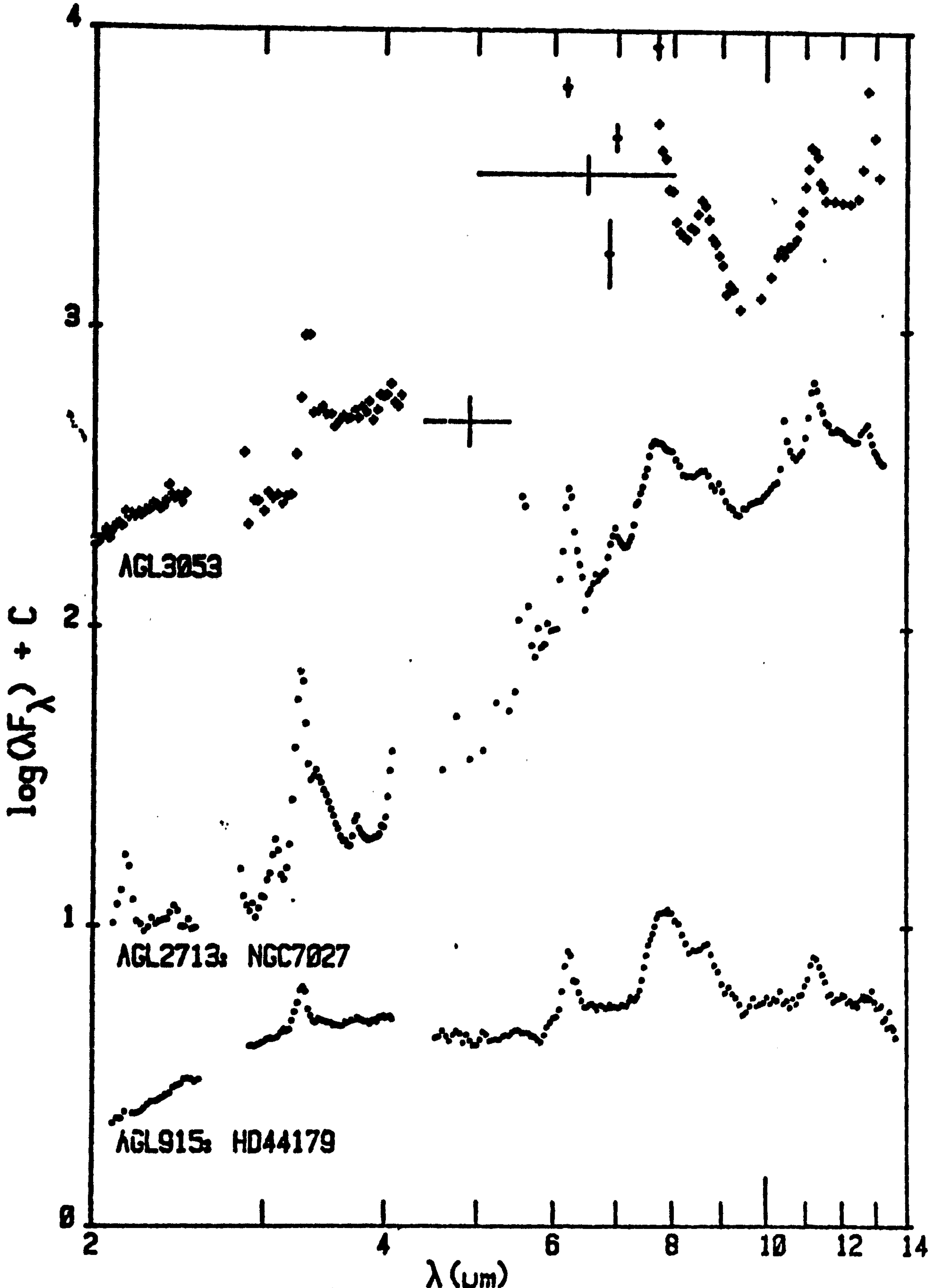

10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\lambda f_\lambda = \nu f_\nu$ (erg cm^{-2} s^{-1})
1000 K
0.3 0.4 0.5 1 2 3 4 5 10
$\lambda (\mu m)$
o ● HM Sge
x CRL 1274
+ V1016 Cyg

FIGURE 11

FIGURE 12



4
3
2
1
0
log(λF_λ) + C
AGL3053
AGL2713: NGC7027
AGL915: HD44179
2
4
6
8
10
12
14
λ(μm)