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SOME PHOTOMETRIC CHARACTERISTICS OF T TAURI STARS AND RELATED OBJECTS

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ABSTRACT. This paper presents a brief review of photometric observations from 1565 Å to 22 microns of Orion population stars. The data indicate irregular light variability and color excesses in all wavelengths. It is discussed some similarities and differences between Herbig Ae/Be stars and classical Be stars. It is concluded that the infrared excesses of T Tauri stars and related objects rise from different sources, such as, thermal radiation from circumstellar dust, bound-bound, free-bound and free-free emission processes originating in a hot ionized gaseous envelope surrounding the stars, infrared companions, and to a lesser extent interstellar extinction.

I. INTRODUCTION

T Tauri stars have been recognized as a distinct class of emission-line variables associated with nebulosity since the 40's (Joy 1942, 1945, 1949). Ambartsumian (1947, 1949, 1952, 1954) was the first one to point out that the T Tauri objects are very young stars of intermediate mass, which have not yet reached an equilibrium state. Also it is clear now that there are several kinds of other peculiar young stars associated physically with nebulosity (Herbig 1960, 1962, 1966).

Herbig and Rao (1972) list 323 stars as certain or probable members of the Orion population for which slit spectrograms or equivalent information are available. A large number of emission-Hα stars, most of which must be Orion population objects have been found in objective-prism surveys of dark clouds and young associations (cf. Henize and Mendoza 1973; Gómez and Mendoza 1976; Mendoza and Gómez 1980). Most probably there are other pre-main-sequence objects which are not very well defined spectroscopically. Thus, it is difficult to assert if they are related to the T Tauri family.

We present some of the main photometric characteristics of the emission-line stars of the Orion population, in this paper.

II. LIGHT VARIATIONS

The first known photometric characteristics of T Tauri stars and related objects was an irregular light curve, mostly found in an examination of only a moderate number of photographs (see for instance Kholopov 1951). It is interesting to recall that the light variations of the group of 11 emission-line stars originally described by Joy (1945) and called by him "T Tauri variables" after one of the brightest members had been detected long before the group was defined by a set of spectroscopic criteria (cf. Herbig 1962).

T Tauri stars occasionally display rapid activity, yet the variations, both rapid and slow, seem to be quite irregular; no periodicity has been confirmed for any member of the class. It should be pointed out that in the past most of the photometric data had been inadequate to rule out periodicity in many instances. Time scales for variations vary from minutes (Kuan 1976; Worden *et al.* 1981) to decades (Bellingham and Rossano 1980). Generally the variations are not periodic in nature, although quasi-periodicities have been reported for some stars (Zaitseva and Lyutyi 1979; Kappelman and Mauder 1980).

Parenago (1950 , 1954) set up a descriptive classification of the forms of the light curves of the Orion Nebula variables. We mention only herein the following. Several T Tauri stars have remained faint for many years with only small light variations, detected mostly in the photographic where they have been extensively observed in the past; suddenly they become several magnitudes brighter. The two well known examples are FU Orionis which prior to 1936 was apparently variable between $m_{ph} = 15.3$ and 16.4 (Hoffleit 1935). FU Ori rose suddenly to $m_{ph} = 10.1$ and by late 1937 was 9.7 (cf. Herbig 1966). V1057 Cygni prior to 1969 was known as one of the faint T Tauri stars associated with the North American Nebula (Herbig 1958). It seems that this remarkable object showed only small light variations (Meinunger and Wenzel 1971; Robinson and Harwood 1971) around $m_{ph} = 16$. In 1969 November, Welin (1971) discovered that V1057 Cyg had increased its brightness to approximately $m_{ph} = 10$. In August 1971 V = 9.47 (Mendoza 1971). At present V is much fainter than the 10-magnitude (Mendoza 1983).

Other well observed T Tauri variables have shown only small erratic light variations, among them T Tauri itself which has been observed in the *UBVRI*-photometric system. We list in Table 1 the range in V magnitude and $(U-B)$, $(B-V)$, $(V-R)$ and $(R-I)$-color indices obtained in three epochs, January 1965 - November 1966 (Mendoza 1968), November 1974 (Cohen and Schwartz 1976) and September 1981 - February 1982 (Herbst *et al.* 1982).

TABLE 1. Light variations of T Tau in *UBVRI*

ΔV	Δ(U-B)	Δ(B-V)	Δ(V-R)	Δ(R-I)	Period	n	Observer
0.22	0.19	0.11	0.20	0.11	Jan. 1965 - Nov. 1966	16	Mendoza (1968)
0.03	0.14	0.05	0.04	0.03	Nov. 1974	6	Cohen and Schwartz (1976)
0.17	0.30	0.11	0.05	0.09	Sep. 1981 - Feb. 1982	14	Herbst *et al.* (1982)

It should be pointed out that this behavior extends at least to the infrared (22 microns) where already there exist many observations at different wavelengths, *JHKLMNQ* and others (cf. Cohen 1973; Gezari *et al.* 1982).

Other Orion population stars show much larger light variations such as CO Ori (Cohen and Schwartz 1976; Herbst *et al.* 1982 for *UBVRI* and Hα; Gezari *et al.* 1982 for longer wavelengths, up to 22μ).

III. COLOR EXCESSES

It had been known for some time, that the colors of T Tauri stars were not normal for their absorption-line spectral types in the sense that the ultraviolet and infrared regions were too bright (Haro and Herbig 1955; Mendoza 1966, 1968).

At present the majority of emission-line stars of the Orion population (Herbig and Rao

1972) have been observed in the infrared, a few of these as far as 160 microns (cf. Gezari *et al.* 1982). The observational data clearly indicate that T Tauri stars and related objects have infrared excesses which cannot be explained by interstellar extinction alone, in most cases.

Two color diagrams are very useful to separate objects with color excesses from other stars. Mendoza (1975) has used (*K-L*) versus (*V-R*) to show a neat separation between stars that belong to O, T, and R associations embedded in or near to dark clouds, and normal main sequence stars. Young stars lie below an interstellar reddening vector of a high ratio of total-to-selective extinction, therefore quite below the main sequence on the (*K-L*, *V-R*)-plane. The larger the displacement, the greater the infrared excess.

Cohen and Kuhi (1979) have used an intrinsic (*H-K*, *K-L*)-diagram for surveying the properties of pre-main-sequence stars. We show in Figure 1 the (*H-K*, *K-L*)-plane, uncorrected for extinction the emission-line stars of the Orion population observed at exactly 1.65, 2.2 and 3.5 microns (Cohen and Kuhi observed at 1.6, 2.3 and 3.5 microns). A good approximation for black-body line is obtained

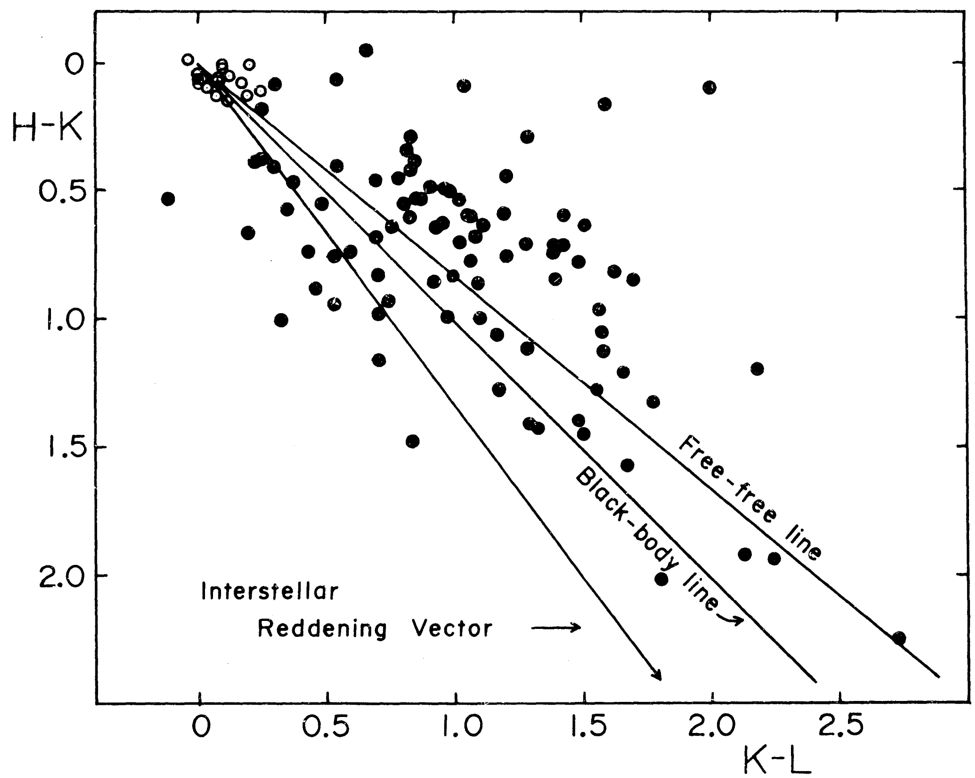

Fig. 1. A two color diagram, near infrared plot for all the T Tauri stars and related objects observed at exactly 1.65, 2.2 and 3.5 microns. Filled circles, Orion population stars. Open circles, Hyades stars. The solid lines illustrate the effects of interstellar extinction, the locus of blackbodies, and free-free emission. Thermal radiation from circumstellar dust effects correspond to the area outside of the free-free line (above and to the right of this line). Some scatter is expected due to light variability in *H*,*K* and *L*.

from $H-K = K-L$ (Allen 1973). Normal stars lie close to this line in the region $H-K < 0.5$ magnitude. In Figure 1 the free-free line indicates the colors of pure free-free radiation for different

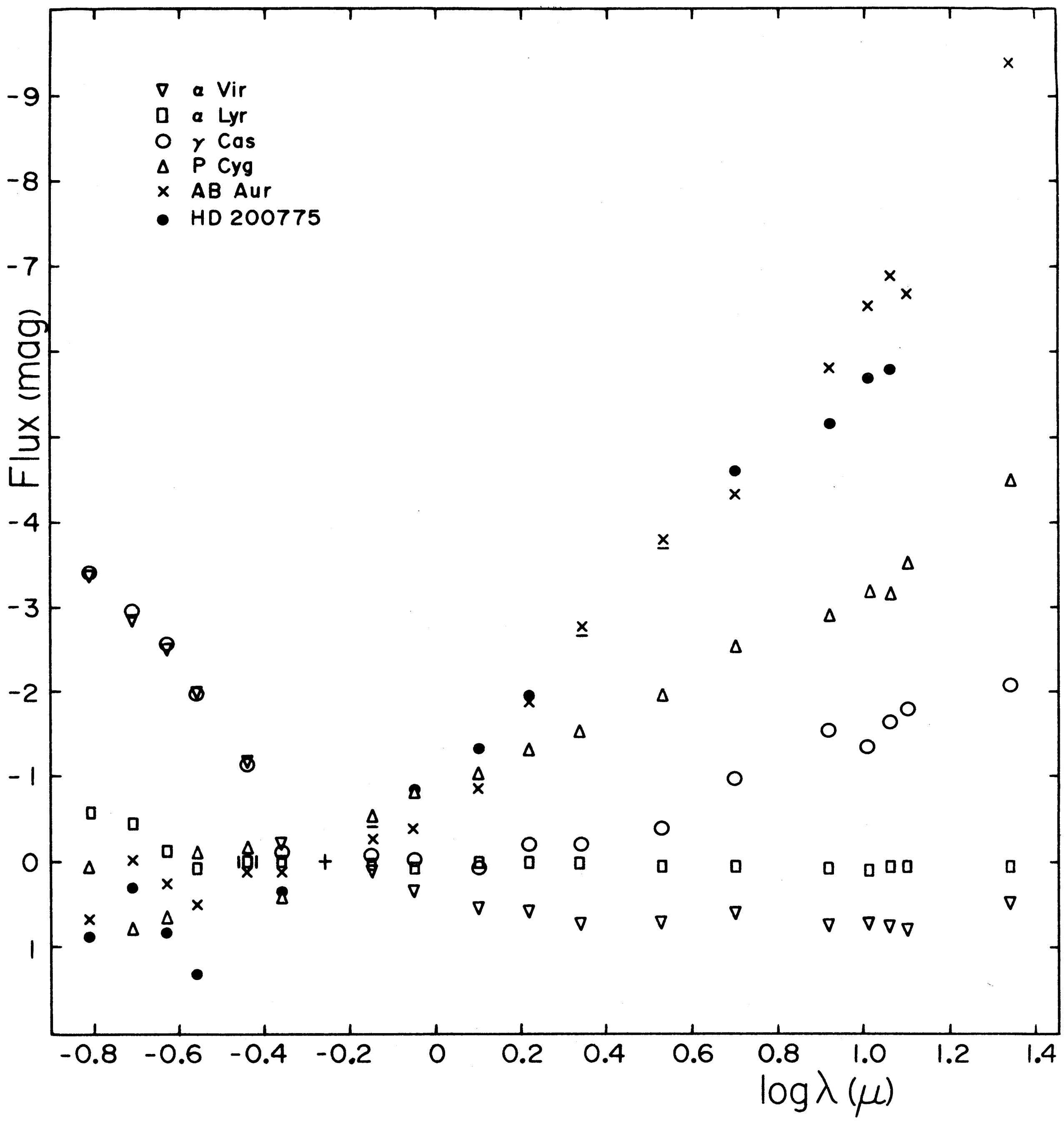

Fig. 2. Observed spectral energy distribution (normalized at V = 0) for two normal stars, two Be stars, and two Herbig Ae/Be stars. The spectral range is from 1565 Å to 22 microns.

values of the electron temperature, T_e, computed from the volume emission coefficient given by Allen (1963). The line labelled interstellar reddening vector is an average of the calculations of van de Hulst (1949) and the observations of stars in Perseus made by Johnson (1965); it is marked at intervals of 10 magnitudes of visual absorption (cf. Allen 1973). It should be pointed out that some scatter is expected in this diagram because of light variability in *H*, *K* and *L*, specially among stars in which *H*, *K* or *L* were not observed simultaneously.

We plot in Figure 2 the observed fluxes in magnitudes, normalized at V = 0, from 1565 Å in the ultraviolet to 22 microns in the infrared for two Herbig Ae/Be stars (AB Aurigae and HD 200775), two Be stars (γ Cassiopeiae and P Cygni) and two main sequence stars (α Lyrae and α Virginis). The *UV* magnitudes are from Thompson *et al.* (1978).

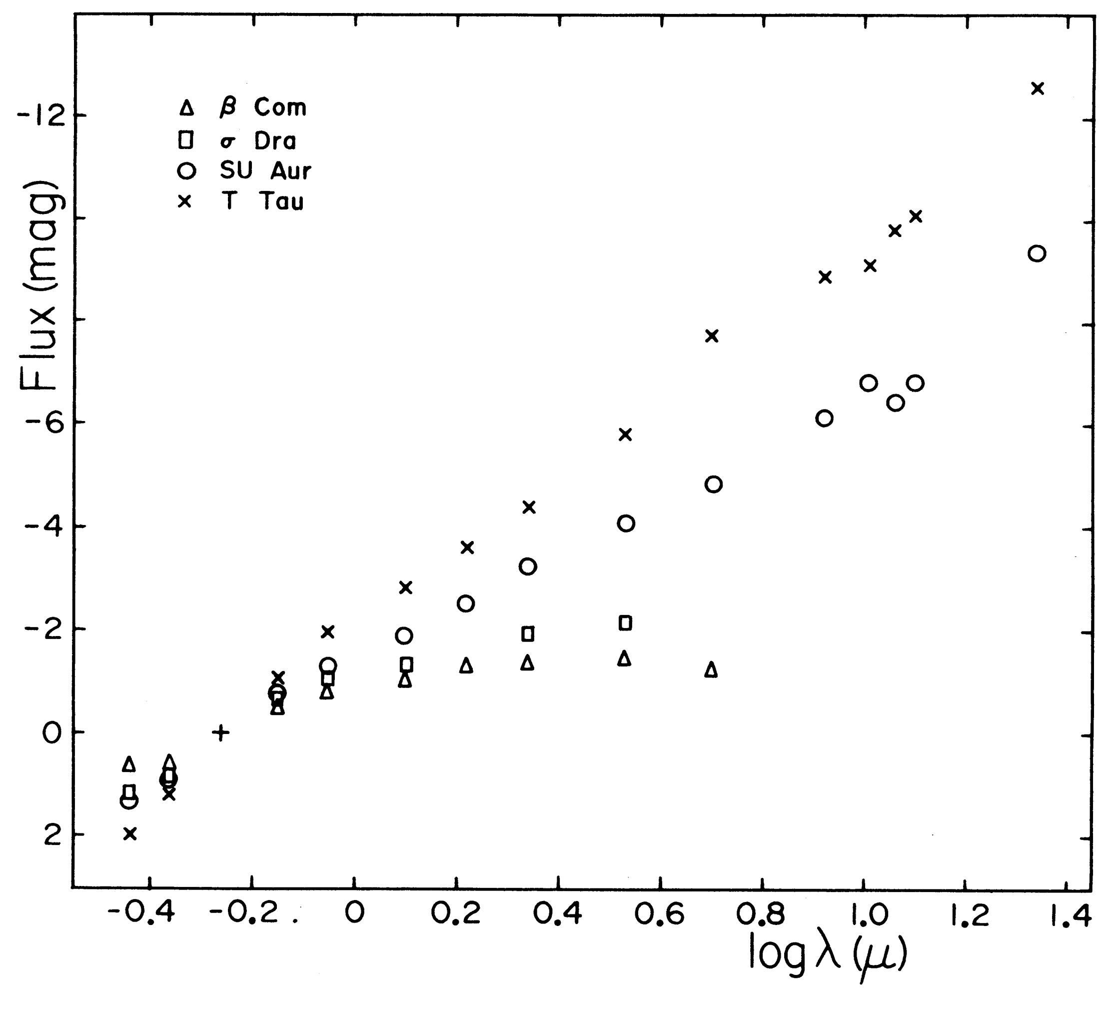

Fig. 3. Observed spectral energy distribution (normalized at V = 0) for two normal stars and two T Tauri stars. The spectral range is from 0.36 to 22 microns.

Next we plot in Figure 3 the observed fluxes in magnitudes, normalized at V = 0, from 0.36 to 22 microns for two T Tauri-like objects (SU Aurigae and T Tauri) and two main sequence stars (β Comae and σ Draconis).

We have smoothed in Figure 4 the data for AB Aur, P Cyg, α Lyr and T Tau (see Figures 2 and 3). We have also added in this figure the observed fluxes of HD 183143, a reddened B7 Ia star (Johnson 1968), and HD 45677 a binary star, its shorter-wavelength radiation comes from a B-type star, the longer from an infrared companion (Low *et al.* 1970).

IV. NARROW BAND PHOTOMETRY

The He I λ10830 Å has been measured by several authors for a number of Herbig Ae/Be stars

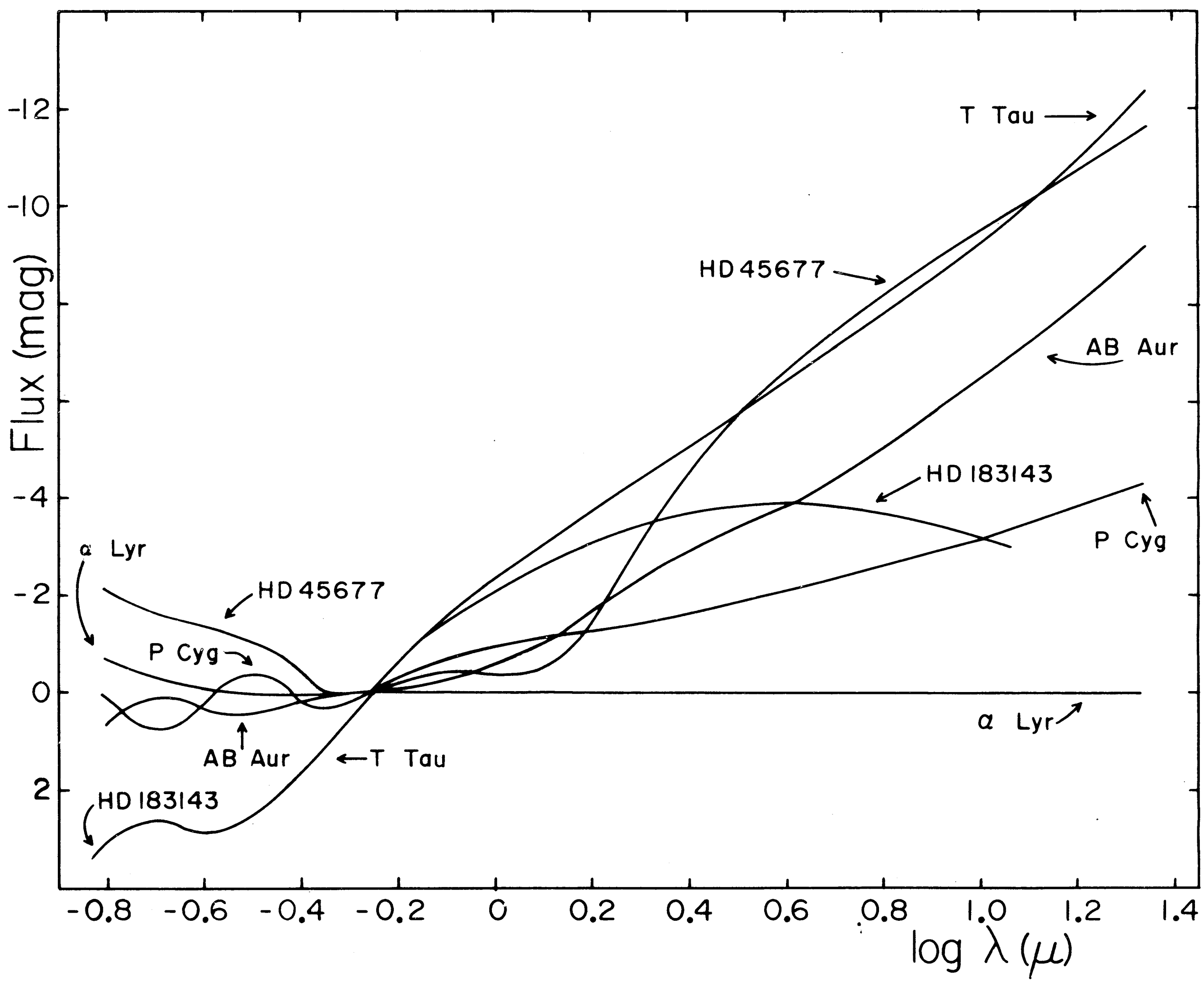

Fig. 4. Smoothed observed spectral energy distribution (normalized at V = 0) for six stars. Four of them selected from Figures 2 and 3; one reddened star, solely by interstellar extinction, probably, and one star with a possible infrared companion, HD 45677.

and other Orion population stars (Zirin 1982; Mendoza 1983). We also have obtained $\alpha(16)\Lambda(19)$-photometry of a number of T Tauri stars and related objects (Mendoza 1976, 1983). Measurements of the Hα-line have been obtained by many observers (cf. Cohen and Schwartz 1976; Rydgren *et al.* 1976; Warner *et al.* 1978; Herbst *et al.* 1982).

The 10830-line may appear with a strong P Cygni profile (Ulrich and Wood 1981; Zirin (1982) e.g., T Tau, and either emission e.g., GW Ori or absorption e.g., SU Aur. We obtain an index that measures the total absorption of this He I line in the same way as we measure the α,Λ-indices (loc.cit) which measure the total absorption of the Hα and OI (λ7774 Å), respectively. Thus, we have no information on the line profile.

The results of the $\alpha(16)\Lambda(9)$-photometry for Herbig Ae/Be stars and T Tauri stars can be summarized in four groups:

1) Stars with a clear absorption in Hα (> 2 Å Eq. W), contaminated with a very weak emission, if any. The OI-line corresponds to a normal main sequence star of the same spectral type, i.e., in absorption, e.g., TY CrA.

2) Stars with a weak Hα-emission which, however, dominates the absorption, if any. The OI-line corresponds to a high luminosity star, i.e., strong absorption, e.g., BS 5999.

3) Stars with a strong Hα-emission and a strong OI-absorption, e.g., LkHα 234.

4) Stars with both, Hα and OI-lines heavily contaminated by emission, e.g., V380 Ori.

It should be pointed out that groups 1, 2 and 4 are also found in the classical Be stars (Mendoza 1981; Mendoza *et al.* 1983). Be stars with a shell fall in group 2, e.g., Pleione.

V. CONCLUSIONS

Several properties of Herbig Ae/Be stars (cf. Herbig 1958; Strom *et al.* 1972; Mendoza 1983) are shared by the "classical" Be stars. Three are noteworthy.

1) Light variations.

2) Color excesses.

3) Emission lines.

In addition, the intrinsic polarization, as function of wavelength resembles that shown by the classical Be stars (Garrison and Anderson 1978).

It should be pointed out, however, that some Herbig Ae/Be stars have larger infrared excesses that any known classical Be star (cf. Figures 1-4), and also in some Herbig Ae/Be stars the Hα and OI (λ7774 Å)-emission is stronger than that of any classical Be star (Mendoza 1981; Mendoza 1983; Mendoza *et al.* 1983). A very interesting difference is the fact that most classical Be stars are not concentrated in the nearby associations but are scattered fairly uniformly along the spiral arm in which the sun is located (Mendoza 1958). On the other hand, Herbig Ae/Be stars are associated with nebulosity, by definition, i.e., they are mostly concentrated in associations.

The irregular light variations, possible at all wavelengths, characteristic of most members of the T Tauri family, may have an origin related to surface changes in the photosphere, or chromosphere (Rydgren *et al.* 1976; Herbst *et al.* 1982). Appenzeller (1983) and Calvet (1983) review the recent indications that the observed activity is produced by flares, spots and related types of surface inhomogeneities.

However, it is also possible that the origin of the light variations are related to circulating dust in any form. Smyth *et al.* (1979) interpret the variability of BS 5999, a Herbig Ae star, due to ejected dust grains. We feel that more systematic observations in Hα, multicolor photometry extended into the infrared, and spectra taken simultaneously, during long periods of time, are needed to decide on the frequency of these or other possible mechanisms.

We conclude, taking into consideration the suggestions made by Mendoza (1966, 1968), Dyck and Milkey (1972), Strom (1972), Milkey and Dyck (1973), Cohen (1974), Glass and Penston (1974), Rydgren *et al.* (1976), Avetisyan *et al.* (1979), Cohen and Kuhi (1979), and many others, as well as Figures 1-4, that the observed infrared color excesses, another photometric characteristic of T Tauri stars and related objects, rise from different sources.

1) *Thermal radiation from circumstellar dust.* It seems that more than a half of the Orion population objects have dust shells (see Figure 1).

2) *Bound-bound, free-bound and free-free emission* processes originating in a hot ionized gaseous envelope surrounding the stars. Perhaps the majority of Herbig Ae/Be stars have ionized gas shells (loc. cit.).

3) *Infrared companions.* In a few cases a considerable fraction of the infrared excess could be due to "infrared" companions, similar to the components of T Tau and HD 45677.

4) *Interstellar extinction.* A number of Orion population stars are reddened by interstellar extinction. It seems that this absorption is a minor contributor for the infrared excess in most cases, nevertheless it has to be taken into account. However, it is not easy to correct it properly (Cohen and Kuhi 1979).

It should be pointed out that each T Tauri star, in more than one way is a unique object. Thus, it is difficult to find characteristics valid for them all.

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DISCUSSION

Herbst: (*Comment*) One of the defining characteristics of Herbig Ae/Be stars is that they illuminate reflection nebulae. However, some (especially early-type ones) show little, if any, light variation. They may be more closely related to classical Be stars, then to T Tauri stars. On the other hand, there are Ae stars (e.g., WW Vul, UX Ori, and BF Ori) which do not illuminate reflection nebulae, but which are variable in ways closely similar to some T Tauri stars. I suggest that the photometric properties of a star (i.e., whether or not is is variable) may be more important than whether or not it illuminates a reflection nebula, in identifying the early-type analogues of the T Tauri stars.

Peimbert: It is possible that binarity might be responsible for the emission activity of Herbig's Ae and Be stars, in particular for those three objects without a reflection nebula that show irregular variations?

Mendoza: Probably not. It is interesting to mention that the duplicity frequency in classical Be stars is high. However, right now I do not remember how it is for Herbig Ae/Be stars.

Pismis: Now that emission B stars are being discussed I consider it an opportunity to ask to anyone a question, the answer of which I have been unable to obtain up to date. I like to know what the order of magnitude is of the absolute energy contained in the Hα-emission line in Be stars, rather the maximum energy radiated. Has this been calculated at all?

Herbig: I do not have that number in my head, but would guess that the extensive study of Ae/Be stars by U. Finkenzeller will provide such information.

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