No. 86 INFRARED PHOTOMETRY OF T TAURI STARS AND RELATED OBJECTS*

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We have begun a multicolor photometric study in wavelengths ranging from 0.36 μ in the ultraviolet to 5.0 μ in the infrared for 26 T Tauri stars and related objects. The study is not complete, but the results are so unexpected that a preliminary report is called for.

All of the observations were obtained with the apparatus described by Johnson and Mitchell (1962), and by Low and Johnson (1964), and with the 28-in. and 60-in. infrared telescopes of LPL.

Seven of the objects under study, imbedded in the Orion Nebula, are difficult to observe because they are faint and the sky background is bright and variable. The *UBVRI* photometry for these stars was carried out with two diaphragms of diameter 18″ and 36″, respectively. The sky readings were taken in four prime positions around each object. The internal agreement is good. We find that the values obtained with both diaphragms are the same for *BVRI* magnitudes, which means that the nebular background was negligible compared with stars. However, the *U* magnitudes of three stars (see below) were very different with diaphragm changes; the *U* values were brighter with the larger diaphragm. All the stars were observed in *JKLM* with only the 18″ diaphragm.

The observational data on the multicolor system defined by Johnson (1964) are listed in Tables 1 and 2. The columns of Table 1 contain: first, the name of the star; second through tenth, the *UBVRIJKLM* magnitudes, respectively; eleventh, the spectral types given by Herbig (1962), Joy (1960), and Haro and Chavira (flare types, 1964); twelfth, the number of different nights on which observations were made (first figure corresponds to *UBVRI* observations; middle figure to *JKL*, and last figure to *M*); and last, Notes. Table 2 contains the $U - V$, $B - V$, $V - R$, $V - I$, $V - J$, $V - K$, $V - L$, and $V - M$ colors of stars in Table 1, and those of the Sun (Johnson 1966).

Our photometric data, combined with the spectral types given in Table 1 and the intrinsic colors given by Johnson (1966), show the following:

a) Ultraviolet excesses for the majority of the stars. The strongest excesses are shown by the latest spectral types. For DF Tau, $E_{U-V} = 2.2$ mag.

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TABLE 1

Magnitudes of T Tauri Stars and Related Objects

Name	*U*	*B*	*V*	*R*	*I*	*J*	*K*	*L*	*M*	Sp	*n*	Notes
BP Tau	12.72	12.89	11.95	10.83	9.85	—	—	—	—	dK5e	1-0-0	
RY Tau	12.20	11.79	10.84	9.94	9.04	—	—	—	—	dGOe	1-0-0	
T Tau	12.44	11.70	10.45	9.33	8.42	7.55	5.53	4.00	2.7	dG5e	13-5-2	1
DF Tau	11.97	12.25	11.42	10.31	9.14	—	—	—	—	dMOe	3-0-0	
DG Tau	12.46	12.84	11.82	10.60	9.52	—	—	—	—	G:e	3-0-0	
UX Tau	11.22	11.83	10.79	9.82	9.04	—	—	—	—	dG5e	2-0-0	
Ton 14	14.97	14.71	13.28	11.47	9.88	—	—	—	—	—	2-0-0	2
UZ Tau	13.74	14.05	12.86	11.21	9.75	—	—	—	—	dMe var	2-0-0	
VY Tau	13.27	13.36	12.49	11.46	10.45	—	—	—	—	—	1-0-0	
UY Aur	12.83	12.97	11.91	10.60	9.53	—	—	—	—	dG5:e	1-0-0	
SU Aur	10.39	9.98	9.09	8.35	7.79	7.2	5.8	4.9	3.5	G2ne III	1-1-2	
RW Aur	10.75	11.00	10.40	9.62	8.90	8.1	6.7	5.6	5.1	dG5e	1-1-1	
CO Ori	12.27	11.62	10.56	9.55	8.76	8.0	6.6	5.6	—	Gpeα	1-1-0	
GW Ori	10.91	10.62	9.66	8.84	8.21	7.5	6.1	5.0	—	dk3e	1-1-0	
P 1353	15.9:	15.6	14.4	13.3	12.7	—	—	—	—	Flare	3-0-0	3,4
EZ Ori	12.84	12.56	11.70	10.89	10.32	9.8	8.7	8.1	—	F9:e V	5-3-0	
P 1553	14.6	14.02	12.86	11.74	10.87	10.1	8.8	8.4	—	Flare	5-2-0	3
P 2078	14.9:	15.0	13.74	12.53	11.58	—	—	—	—	Flare	4-0-0	3,5
P 2172	15.98	15.26	13.93	12.56	11.35	—	—	—	—	Flare	2-0-0	3
P 2305	16.04	14.86	13.54	12.34	11.48	10.7	9.7	8.8	—	Flare	3-1-0	3
P 2347	15.4:	15.03	13.97	12.83	12.13	—	—	—	—	Flare	4-0-0	3,6
V 380 Ori	10.50	10.70	10.26	9.57	8.84	7.9	5.9	4.4	2.9	A1:e	1-1-1	7
P 2441	11.66	11.43	10.75	10.14	9.68	—	—	—	—	F5:e	1-0-0	3
P 2455	17.5	16.18	14.49	12.60	11.12	—	—	—	—	Flare	3-0-0	3
R Mon	12.34	12.45	11.89	11.13	10.22	8.6	5.3	3.1	1.9	Ge	1-1-1	8
LkHα 120	13.37	12.97	11.96	10.98	10.23	—	—	—	—	—	3-0-0	9

NOTES TO TABLE 1

1. The $(U - B)$ range was from +0.63 to +0.83, from January to December 1965. Kuhi (1964) says that a high-dispersion spectrum of T Tau (by Herbig) gives a K1 type.
2. Haro, Iriarte, and Chavira 1953.
3. Parenago 1954.
4. Mean $(U - B)$ of −0.30 and +0.94; see text.
5. Mean $(U - B)$ of −1.00 and +0.83; see text.
6. Mean $(U - B)$ of +0.05 and +0.78; see text.
7. *UBVRI* photometry made with a 36″ diaphragm.
8. *UBVRI* photometry made with a 27″ diaphragm.
9. Herbig 1962.

TABLE 2

Colors of T Tauri Stars, Related Objects, and the Sun

Name	*U—V*	*B—V*	*V—R*	*V—I*	*V—J*	*V—K*	*V—L*	*V—M*
BP Tau	0.77	0.94	1.12	2.10	—	—	—	—
RY Tau	1.36	0.95	0.90	1.80	—	—	—	—
T Tau	1.99	1.25	1.12	2.03	2.90	4.92	6.45	7.7
DF Tau	0.45	0.83	1.11	2.28	—	—	—	—
DG Tau	0.64	1.02	1.22	2.30	—	—	—	—
UX Tau	0.43	1.04	0.97	1.75	—	—	—	—
Ton 14	1.71	1.43	1.81	3.40	—	—	—	—
UZ Tau	0.88	1.19	1.65	3.11	—	—	—	—
VY Tau	0.78	0.87	1.03	2.04	—	—	—	—
UY Aur	0.92	1.05	1.31	2.38	—	—	—	—
SU Aur	1.30	0.89	0.74	1.30	1.9	3.3	4.2	5.6
RW Aur	0.35	0.60	0.78	1.50	2.3	3.7	4.8	5.3
CO Ori	1.71	1.06	1.01	1.80	2.6	4.0	5.0	—
GW Ori	1.25	0.96	0.82	1.45	2.2	3.6	4.7	—
P 1353	1.5:	1.2	1.1	1.7	—	—	—	—
EZ Ori	1.14	0.86	0.81	1.38	1.9	3.0	3.6	—
P 1553	1.7	1.16	1.12	1.99	2.8	4.1	4.5	—
P 2078	1.2	1.3	1.21	2.16	—	—	—	—
P 2172	2.05	1.33	1.37	2.58	—	—	—	—
P 2305	2.50	1.32	1.20	2.06	2.8	3.8	4.7	—
P 2347	1.4:	1.06	1.14	1.84	—	—	—	—
V 380 Ori	0.24	0.44	0.69	1.42	2.4	4.4	5.9	7.4
P 2441	0.86	0.68	0.61	1.07	—	—	—	—
P 2455	3.0	1.69	1.89	3.37	—	—	—	—
R Mon 0.45	0.45	0.56	0.76	1.67	3.3	6.6	8.8	10.0
LkHα 120	1.41	1.01	0.98	1.73	—	—	—	—
Sun*	0.70	0.64	0.52	0.78	1.06	1.41	1.53	1.40

*$V = -26.74$.

b) Blue excesses for those stars with the largest ultraviolet excesses. For DF Tau, $E = 0.6$ mag.

Earlier UBV photometry of T Tauri stars and related objects (Bretz — see Whitford 1960; Varsavsky 1960; Smak 1964*a*) has shown the same general feature, namely, an ultraviolet excess. At the present time, there is no doubt that these excesses are caused by line and continuum emission in both $U - B$ and $B - V$ colors.

c) Red excesses for the majority of the stars. Notice that DF Tau shows a "deficiency" ($E_{V-R} = 0.2$), most likely caused by the effect of the Hα-line in emission in the V magnitude.

d) Infrared excesses (from 0.9 μ to 5.0 μ) for all the stars. $E_{V-M} = 6.2$ mag for T Tau and $E_{V-M} = 8.5$ mag for R Mon!

If these infrared excesses were caused mostly by interstellar extinction, then the total absorption, $A_v \gtrsim E_{V-M}$, would be very high and the stars would either be very near (T Tau and R Mon would be closer than 20 pc) or too luminous for their spectral types ($M_v = -7$ mag for R Mon).

The spectral energy-curves for T Tau, R Mon, and the Sun are shown in Figure 1. The ones for V 380 Ori and α Lyr are shown in Figure 2. They were computed with the aid of the absolute calibration derived by Johnson (1965*a*) and have been normalized to unity at the maxima. T Tau, V 380 Ori, and R Mon show the strongest infrared excesses. These three objects illuminate bright nebulosity (Herbig 1962). The photometric errors are such that the general features shown in Figures 1 and 2 are not affected appreciably by them.

We have computed the bolometric corrections, B. C., for T Tau, V 380 Ori, and R Mon following the procedure outlined by Johnson (1964). This procedure consists primarily of a simple numerical integration under the spectral energy distribution after conversion to absolute units. The results of this integration are then compared with the corresponding values for the Sun. For this computation, we have assumed that the $N(10\ \mu)$ magnitudes are equal to the $M(5\ \mu)$ magnitudes and that the radiation from wavelengths longer than 14 μ is negligible. Both assumptions probably will cause underestimates of the total radiation flux. The results are given in Table 3. The columns of this table contain: first, the name of the object; second, the bolometric corrections; third, the newly determined distances (John-

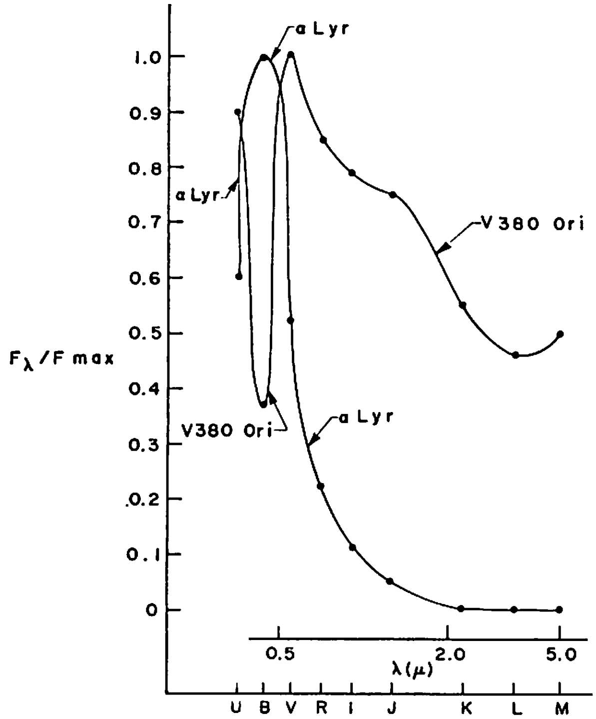

Fig. 2 The spectral energy-curves for α Lyr and V 380 Ori (Al:e), a marginal T Tauri star (Herbig 1962). V 380 Ori illuminates NGC 1999 (Morgan and Sharpless 1946; Herbig 1960).

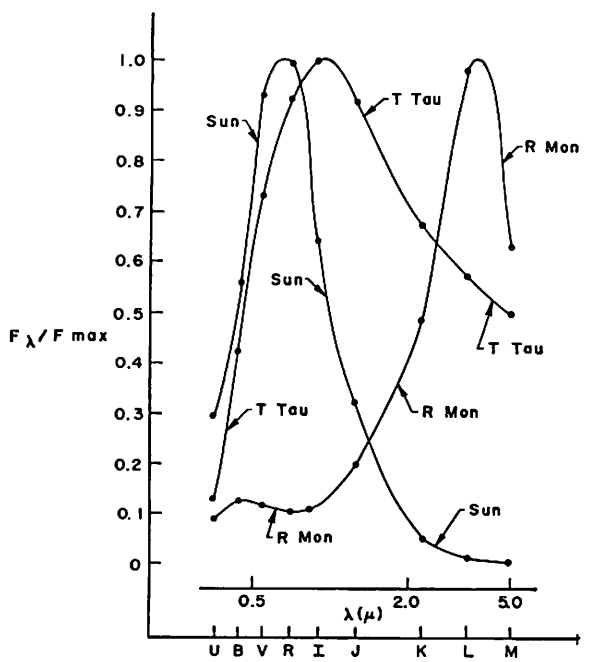

Fig. 1 The spectral energy-curves for the Sun, T Tau, and R Mon. T Tau illuminates NGC 1555 (Hind's nebula). R Mon illuminates NGC 2261 (Hubble's nebula) (see Herbig 1960, 1962).

TABLE 3

BOLOMETRIC CORRECTIONS FOR THREE T TAURI STARS

NAME	B.C.	r(pc)	M_{bol}
T Tau	−2.6	150	+2.0
V 380 Ori	−2.2	380	+0.2
R Mon	−4.2	690	−2.0

son 1965*b*); and fourth, the absolute magnitude uncorrected for interstellar absorption. Herbig (1960) gives very good reasons for believing that V 380 Ori is at the same distance as the Orion Nebula, and R Mon is at the same distance as NGC 2264. The values of the absolute magnitudes given in Table 3 were computed under these assumptions. For T Tau, we have used the distance of the Taurus cloud (e.g., Smak 1964*a*). These absolute magnitudes most probably are lower values since the apparent bolometric magnitudes might be undercorrected, and no correction for interstellar extinction was made.

We can interpret our photometric data (see Figs. 1 and 2) as follows:

a) As measures for the combination of two or more stars. For example, one solar-type star and one infrared star, like the Neugebauer-Martz-Leighton (1965) Cygnus object or TX Cam (Mendoza V. 1965), would give us a spectral energy-curve very similar to the one shown in Figure 1 for R Mon.

b) The short-wavelength photometry refers to a small core and long-wavelength photometry to a large envelope.

Several long-period variables are known to have companions. For instance, R Hya (M6e) has a K-dwarf companion (Smak 1964*b*). Thus, if assumption (*a*) is correct, it might be that long-period variables are young stars.

We also can see that an infrared star with a spectral energy-curve similar to R Mon (see Fig. 1) at a distance of, say, 690 pc would be several magnitudes above the zero-age main sequence and far to the right in the plane (M_{bol}, T_e). Such a star could be called a protostar (Hayashi 1961) since it is believed that T Tauri stars themselves are very young stars (see, e.g., Huang 1964).

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