

A Deep Objective Prism Survey for Classical T Tauri Stars in the Sigma Orionis Region

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ABSTRACT

A very deep 1976 CTIO Curtis Schmidt objective prism plate of the Sigma Orionis Association taken under excellent conditions has permitted us to search for fainter classical T Tauri stars associated with this cluster. We have discovered 63 H-alpha emission stars in the area to a limiting magnitude of about 18. Most of these stars are new additions to the growing list of Pre-Main-Sequence objects identified in this very dense, very young cluster. Since T Tauri stars vary in light and emission-line strength on all time scales, these data also provide an historical record of the association. By comparison with later observations, we are able to estimate the average space density of the H α emission-line stars in the surveyed area as between 0.52 and 0.86 pc⁻³ down to a spectral class of dM0. This is about 1/3 of the number of dwarf or subgiants stars in the region that could have been detected as emission-line stars in these surveys.

Subject headings: stars: formation, stars: emission-line, stars: pre-main-sequence

1. Introduction

In 1967, Garrison (1967) classified 15 B-type stars in the vicinity of the star σ Ori-
onis. He found an extremely narrow main
sequence and a distance modulus of 8.2
magnitudes. In 1976 the first author took
a series of CTIO Curtis Schmidt plates of

the area. The large number of emission-
line objects in the region of σ Ori
was noted but since the majority of the objects were
too faint for follow-up spectroscopic obser-
vations with the detectors of that era with
the MIRA 36-inch telescope, no further ac-
tion was taken. The cluster was recog-
nized by the Lund Observatory Catalogue
of Open Clusters in 1981.

Recent work by Wolk (1996) and Wal-
ter et al. (1998), and an H-alpha survey
of the area by the Kiso group (Nakano et

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al. (1995), Wiramihardja et al. (1989), & Wiramihardja et al. (1991)) inspired us to re-visit the Schmidt observations (Babcock & Weaver (2000), hereafter BW). In the last few years, this region has proved to be a rich area for searches for a substellar population (e.g., Tej et al. (2002), Barrado y Navascués et al. (2003)) as well as pre-main-sequence objects because of its modest distance modulus (7.7, *Hipparcos*) and low reddening (Béjar et al. 1999).

2. Observations

The observations discussed below are based on a 75 minute, unwidened, 6-degree objective prism exposure taken with the 24/36-inch Curtis Schmidt on 19/20 November, 1976. A baked 127-04 plate behind an RG-2 filter was used.

The plate was taken under excellent seeing conditions and the limiting red magnitude is approximately 18th magnitude. The area surveyed extends about 1 degree around σ Ori, or about 6 parsecs at the association based on a *Hipparcos* distance of 352 parsecs (Béjar et al. 1999). Unfortunately, the northern limit of the survey is defined at about declination $-2^{\circ} 10'$ by the physical plate limit, clearly before the association ends in that direction. The search was limited in the other directions only when the density of detected emission-line objects became very low. Regrettably, the capability to extend these observations is no longer available. The positions of the H-alpha emission-line stars identified by this survey are shown in Figure 1.

The detailed results of the survey are shown in Table 1. Positions for most of the objects were obtained by identifying them with the USNO-A2.0 catalog; a few others

were derived from the sources described in the notes to Table 1. Where a ‘v’ magnitude was available for Kiso objects, it was taken as the apparent V magnitude (m_V); otherwise it was identified with Aladin and the V magnitude was taken from the catalogues available to it or from Simbad using the Aladin-confirmed position. For a few stars direct V magnitudes were not available because of associated emission nebulosity. In these cases, J magnitudes from 2MASS were used to infer the spectral types at the *Hipparcos* distance modulus and the apparent V magnitudes were derived from that determination. As all these objects are probably variables, this seems adequate for the purposes of this investigation. The magnitudes determined in this latter manner are marked as uncertain.

The relative strengths of the continuum and emission are noted. Those stars with continua classified as ‘strong’ had an average V magnitude of 13.7 ± 1.0 ; ‘medium’ 14.5 ± 0.7 ; and ‘weak’ 15.2 ± 1.0 standard deviation. The emission described as ‘very weak’ should be used with caution; however, the position of these marginal detections coincided with the expected off-set position of the H α line from the direct star position.

3. Results

A total of 63 H α emission-line stars were identified in this survey; 38 of them are newly discovered and 25 had already been identified in the Kiso (Wiramihardja et al. (1989) & Wiramihardja et al. (1991)) surveys. The distributions of the BW and Kiso stars by magnitude are shown in Figure 2. The current survey seems slightly

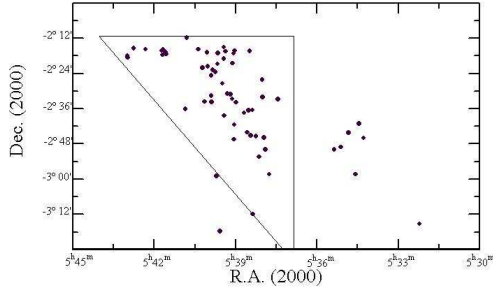


Fig. 1.— The observed area. The triangle denotes the area used for calculations in the results section.

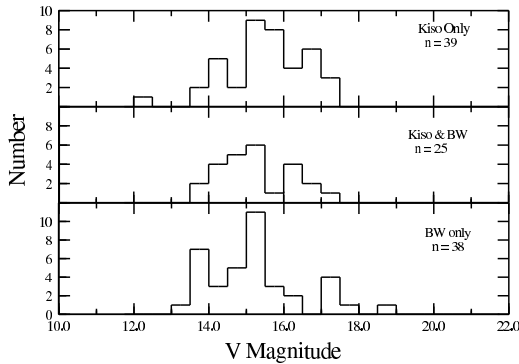


Fig. 2.— Distributions of $H\alpha$ emission-line star visual magnitudes discovered by the BW and KISO surveys.

fainter than that of Kiso. This is not surprising considering the excellent conditions under which the BW plate was taken.

Herbst et al. (2002) found from their photometric monitoring of the Orion Nebula stars that essentially all the stars in the field are variable. This agrees with the observation derived from spectroscopic studies that surveys of T Tauri associations taken at different times invariably discover new emission-line stars. With independent spectroscopic surveys at two widely separated epochs, an estimate can be made of the total population of emission-line stars in the region.

If one assumes that the decade between our observations and those of Kiso is sufficiently long that the probability of these stars being in emission is independent between the two epochs, one can make an estimate of the total number of such objects in the area:

$$N_{total} = \frac{(N_1 N_2)}{(N_1 \cap N_2)}$$

where N_i are the number of stars detected by each survey. We truncate the number of BW stars at $V = 17.5$ to match the apparent Kiso limit. Using the numbers from Figure 2, the total estimated number of $H\alpha$ stars to about dM0 in the region outlined in Figure 1 of the σ Orionis association is 156.

Assuming a depth comparable to the characteristic dimensions of the projected size of the area surveyed, the volume of the area under consideration is taken as 300 pc^3 . Thus the space density of the 102 emission-line objects discovered in this region corresponds to an average space density of about 0.34 pc^{-3} to a spectral class

of dM0 (V=16.5 without reddening at the σ Orionis association). For the assumed full 156 stars estimated for this region, the average space density would be 0.52 pc^{-3} . Figure 1 shows that local densities are often much higher.

The decade span may not be longer than the time for significant changes in the emission strengths in some of the stars so the above estimate can be taken as a lower limit. A better approximation would be

$$N_{total} = \frac{(N'_1 + S) \times (N'_2 + S)}{S} + A$$

where N'_i is the number of stars detected *only* by the i^{th} survey and S is the number of the $N_1 \cap N_2$ stars that do vary in this time frame and A is the number of $N_1 \cap N_2$ stars that do not. A, the number of stars which are constantly in emission, is treated as that fraction of $N_1 \cap N_2$ stars that are completely counted. If $S \geq 1$ then this sets the upper limit of N_{total} as about 1500. Even if only a third of the stars detected by both surveys were variable in the time period, the total number of these stars in the area would be about 250, corresponding to a space density of T Tauri stars in this volume of 0.86 pc^{-3} .

In order to estimate the fraction of objects in the area which are emission-line objects at some time, we can make a rough estimate of the number of cool, and/or reddened luminosity class IV or V stars in the region outlined in Figure 1. There are 5014 stars in the USNO A2.0 catalog in this region of which 952 stars have an R magnitude brighter than 16, roughly corresponding to an m_V limit of 17.5 at the association. The USNO A2.0 catalog gives B and R magnitudes. Of the 952 objects, 567 are

redder than the B-R vs R line for dwarf or subgiant stars, minus 0.5 magnitudes for observational errors and cosmic scatter, at the distance to the cluster. This technique would work best for a region more uniformly opaque than the σ Orionis Association, where some of this final number will be background red giants found in the more transparent patches .

Thus, it appears that there are about three times as many potential PMS stars in the σ Orionis association than the estimated total number of H α emission-line stars.

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TABLE 1
SIGMA ORIONIS EMISSION-LINE STARS.

Star	RA (2000)	Dec (2000)	Source ^a	magnitude			Aladin			Kiso	
				mag	type	source	m_V	Emission	Continuum	ID	Note ^b
1	5 ^h 32 ^m 12. ^s 9	-3°15'15"	1	15.2	red	USNO	14.2	weak	medium		
2	5 ^h 34 ^m 16. ^s 6	-2°45'53"	4	16.4	red	POSS	17:	v.weak:	none		
3	5 ^h 34 ^m 26. ^s 7	-2°41'07"	1	16.2	red	USNO	15.1	v.weak	weak		
4	5 ^h 34 ^m 34. ^s 2	-2°58'16"	1	16.3	red	USNO	15.1	weak	none		
5	5 ^h 34 ^m 50. ^s 0	-2°44'08"	1	16.4	red	USNO	15.1	medium	weak		
6	5 ^h 35 ^m 07. ^s 6	-2°49'00"	1	14.3	red	USNO	13.5	medium	medium		
7	5 ^h 35 ^m 21. ^s 7	-2°49'54"	1	15.7	v	Kiso	14.4:	strong	medium	A-0976	152
8	5 ^h 37 ^m 26. ^s 2	-2°32'44"	1	14.7	red	USNO	13.8	v.weak:	medium		
9	5 ^h 37 ^m 45. ^s 5	-2°58'21"	1	15	red	USNO	14.0	weak	weak		
10	5 ^h 37 ^m 54. ^s 0	-2°49'55"	1	16.4	red	USNO	15.3	weak	none		
11	5 ^h 37 ^m 57. ^s 6	-2°45'47"	1	16.2	red	USNO	15.0	weak	v.weak		
12	5 ^h 38 ^m 00. ^s 8:	-2°32'04"	4				14.6:	v.weak:	medium		
13	5 ^h 38 ^m 01. ^s 0	-2°26'08"	1	15.6	red	USNO	14.5	v.weak:	v.weak		
14	5 ^h 38 ^m 08. ^s 4	-2°52'24"	1	14.6	red	USNO	13.8	medium	weak		
15	5 ^h 38 ^m 15. ^s 1	-2°45'19"	1	17.9	red	USNO	16.4	strong	weak		
16	5 ^h 38 ^m 22. ^s 5	-3°11'57"	1	16.1	v	Kiso		strong	weak	A-0976	327: *
17	5 ^h 38 ^m 23. ^s 1	-2°36'27"	1	16.4	v	Kiso		strong	weak	A-0904	69
18	5 ^h 38 ^m 27. ^s 2	-2°45'10"	1	14.2	v	Kiso		strong	weak	A-0976	328
19	5 ^h 38 ^m 29. ^s 2	-2°16'16"	1	14.3	v	Kiso		medium	weak	A-0904	70 *
20	5 ^h 38 ^m 31. ^s 3	-2°36'33"	2	15.1	v	Kiso		strong	weak	A-0904	71 *
21	5 ^h 38 ^m 34. ^s 6	-2°44'04"	1	14.8	red	USNO	13.9	strong	strong		
22	5 ^h 38 ^m 41. ^s 3	-2°37'23"	3	13.8	red	POSS	13.7:	weak	strong		*
23	5 ^h 38 ^m 59. ^s 2	-2°33'52"	1	15.4	v	Kiso		medium	weak	A-0904	74
24	5 ^h 39 ^m 02. ^s 0	-2°16'13"	1	17.2	red	USNO	15.8	medium	weak		
25	5 ^h 39 ^m 02. ^s 9	-2°41'26"	3	14.9	red	POSS	15.2:	weak	weak		*
26	5 ^h 39 ^m 03. ^s 6	-2°46'27"	1	16.7	red	USNO	15.3	weak	weak		
27	5 ^h 39 ^m 04. ^s 8	-2°17'07"	1	14	red	USNO	13.3	v.weak	weak		
28	5 ^h 39 ^m 07. ^s 3	-2°20'27"	1	15.5	red	USNO	14.4	v.weak	weak		
29	5 ^h 39 ^m 07. ^s 6	-2°32'39"	1	13.9	v	Kiso		medium	medium	A-0904	77
30	5 ^h 39 ^m 11. ^s 5	-2°31'06"	1	15.4	v	Kiso		strong	medium	A-0904	78 *
31	5 ^h 39 ^m 18. ^s 8	-2°30'53"	1	14.6	v	Kiso		weak	medium	A-0904	81
32	5 ^h 39 ^m 22. ^s 3	-2°16'26"	1	16.4	red	USNO	15.2	v.weak:	weak		
33	5 ^h 39 ^m 25. ^s 2	-2°38'22"	1	14.3	red	USNO	13.6	strong	medium		
34	5 ^h 39 ^m 26. ^s 0	-2°18'56"	1	17.6	red	USNO	16.1	v.weak:	weak		
35	5 ^h 39 ^m 26. ^s 4	-2°15'03"	1	14.7	v	Kiso		weak	weak	A-0904	84
36	5 ^h 39 ^m 29. ^s 6	-2°27'22"	1	14.6	v	Kiso		medium	none	A-0976	351
37	5 ^h 39 ^m 34. ^s 5	-3°17'48"	1	16.3	v	Kiso		strong	weak	A-0976	353
38	5 ^h 39 ^m 39. ^s 4	-2°17'05"	1	15.8	red	USNO	14.7	strong	medium		
39	5 ^h 39 ^m 40. ^s 2	-2°20'48"	1	14.1	v	Kiso		medium	medium	A-0904	91
40	5 ^h 39 ^m 42. ^s 8	-2°58'54"	1	14	v	Kiso		medium	strong	A-0976	358
41	5 ^h 39 ^m 44. ^s 9	-2°23'26"	1	17.1	red	USNO	15.7	weak	v.weak		
42	5 ^h 39 ^m 51. ^s 7	-2°22'47"	1	16	red	USNO	14.9	medium	none		
43	5 ^h 39 ^m 53. ^s 6	-2°33'43"	1	16.3	v	Kiso		strong	weak	A-0976	359
44	5 ^h 39 ^m 53. ^s 7	-2°31'35"	1	15.9	red	USNO	14.7	strong	strong		
45	5 ^h 39 ^m 54. ^s 3	-2°24'39"	1	14.7	v	Kiso		strong	medium	A-0904	93 *
46	5 ^h 40 ^m 01. ^s 9	-2°21'33"	1	16.8	v	Kiso		medium	weak	A-0904	95 *
47	5 ^h 40 ^m 03. ^s 7	-2°16'46"	1	14.7	v	Kiso		medium	medium	A-0904	97
48	5 ^h 40 ^m 08. ^s 9	-2°33'34"	1	15.4	v	Kiso		strong	weak	A-0976	364
49	5 ^h 40 ^m 12. ^s 9	-2°22'02"	1	13.6	v	Kiso		medium	strong	A-0904	101
50	5 ^h 40 ^m 22. ^s 5	-2°15'40"	1	14.5	red	USNO	13.7	medium	weak		
51	5 ^h 40 ^m 48. ^s 2:	-2°11'47"	4				15.2:	medium	weak		
52	5 ^h 40 ^m 51. ^s 4	-2°36'02"	2	17.4	v	Kiso		strong	none	A-0904	111 *

TABLE 1—*Continued*

Star	RA (2000)	Dec (2000)	Source ^a	magnitude			Aladin	Emission	Continuum	Kiso	Note ^b
				mag	type	source	m_V			ID	
53	$5^h41^m33.^s8$:	$-2^\circ17'22''$:	4	16.2	red	POSS	17:	v.weak:	v.weak		
54	$5^h41^m36.^s4$	$-2^\circ16'46''$	3	15	red	est.	15.2:	medium	weak		
55	$5^h41^m40.^s4$	$-2^\circ15'58''$	3	11.3	J	2MASS	14.6:	medium	medium		
56	$5^h41^m42.^s3$	$-2^\circ17'35''$	3	12.3	J	2MASS	17:	weak	v.weak		
57	$5^h41^m43.^s1$	$-2^\circ17'38''$	3	13	J	2MASS	15.2:	v.weak	weak		
58	$5^h41^m44.^s2$	$-2^\circ16'16''$	3	12.8	J	2MASS	17:	medium	v.weak		
59	$5^h41^m41.^s5$	$-2^\circ15'42''$	3	14.1	J	2MASS	17.5:	weak	none		
60	$5^h42^m19.^s5$	$-2^\circ15'41''$	1	16.6	v	Kiso		strong	weak	A-0904 136	
61	$5^h42^m45.^s8$	$-2^\circ15'23''$	1	15.4	v	Kiso		strong	medium	A-0904 143	
62	$5^h42^m58.^s5$	$-2^\circ18'05''$	3	15.4	J	2MASS		weak	weak		
63	$5^h42^m58.^s7$	$-2^\circ18'37''$	2	12.1	v	Kiso	15.2:	strong	strong	A-0904 145	

^aposition sources. 1: USNO-A2.0; 2: Kiso; 3: Aladin; 4: Estimated from concurrent CTIO direct plate

^bstar bw16: is $8''$ from Kiso obj; bw19: also Kiso A-0976 330; bw20: also Kiso A-0976 334; bw22: nebulous; bw25: nebular, E of pair is at $5^h39^m03.^s0, -2^\circ41'28''$; bw30: also Kiso A-0976 346; bw45: also Kiso A-0976 360; bw46: also Kiso A-0976 362; bw52: double star, E w/continuum, W w/o; bw63: also Kiso A-0976 38.