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Rotation Periods of Nine ROSAT Selected Solar-Type Stars *

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Abstract We monitored 16 X-ray selected young solar-type stars for light variation and found appreciable periodic light variability with amplitudes of a few hundredths of a magnitude in nine of the objects. Using the method of Phase Dispersion Minimization (PDM) and Fourier analysis (software PERIOD04), the rotation periods of these stars were determined from the photometric data. The rotation periods of all nine stars are shorter than about 3 days. It is suggested that, as with the Pleiades cluster, small amplitude light variations are quite common among young solar-type stars with rotation periods around 3 days or less. This gives further evidence for the spin up of solar-type stars predicted by models of angular momentum evolution of pre-main sequence stars.

Key words: stars: late-type — stars: pre-main sequence — stars: rotation

1 INTRODUCTION

T Tauri stars (TTSs) are young ($\leq 10^8$ yr), low-mass ($M \leq 2M_\odot$), late spectral type (typically G0 or later) pre-main sequence (PMS) stars. It is well-known that TTSs are photometric variables (Joy 1945). These stars were originally classified as irregular variables whose periods span from minutes to decades and amplitudes from a few magnitudes down to a few hundredths (Herbig 1962; Herbst 1994). The variations of up to several magnitudes are interpreted as the results of accretion and, perhaps, occultation events within the dusty and gaseous disks surrounding classical T Tauri stars (CTTSs). One also sees periodic light variations in weak-line T Tauri stars (WTTSs) and other young solar-type stars that may be largely or entirely attributed to cool (magnetic) spots on the stellar surface (Herbst et al. 1994). Photospheric spots modulate the light curves at the rotation period of the stars and thus allow the rotation period to be derived by photometric observation.

Up to now, photometric surveys in star formation regions and young open clusters have resulted in the detection of several hundred WTTSs with periodic light variation and the youngest dwarfs (Bouvier et al. 1993, 1995; Grankin et al. 1995; Prosser et al. 1995; Shevchenko et al. 1998; Herbst et al. 2000; Lawson et al. 2001; Xing et al. 2006). Their measurements are helpful to the investigation of the rotation rates of stars by placing constraints on the evolution of the angular momentum of stars. They are also helpful in relating chromospheric activity to coronal activity. However, the number of short-period ($<$1 d) stars is very small, especially, there is a gap in periods between one day and a few hours, or, a blank between the oldest TTSs and the youngest solar-type variable stars. This calls for further efforts on the search for more fast-rotating samples.

As the models predict spin-up for stars on their PMS radiative tracks, Bouvier et al. (1997) for the Taurus star formation region and Wichmann et al. (1998) for the Lapus one respectively showed that most of

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Table 1 The 16 ROSAT X-ray Sources

Objects	RA (α2000)	DEC (δ2000)	$B-V$ (mag)	V (mag)	cts s^{-1}
1	2	3	4	5	6
1RXS J004005.0+501414	00 40 06.3	+50 14 15	0.770	10.88	0.0925
1RXS J015627.3+122455	01 56 27.3	+12 24 55	0.598	10.55	0.133
1RXS J032547.5+365147	03 25 47.9	+36 51 47	0.803	13.01	0.0676
1RXS J035201.9+243949	03 52 01.9	+24 39 49	0.60	12.46	0.0538
1RXS J034629.2+242605	03 46 28.4	+24 26 03	0.797	11.10	0.0505
1RXS J040010.0+081830	04 00 09.3	+08 18 13	0.747	10.12	0.363
1RXS J050436.0+040236	05 04 36.1	+04 02 37	0.742	10.49	0.15
1RXS J222007.2+493014	22 20 06.9	+49 30 13	0.846	8.57	0.103
1RXS J235810.1+673356	23 58 10.1	+67 33 56	0.708	8.74	0.835
1RXS J005708.1+102554	00 57 07.6	+10 25 56	0.721	10.07	0.297
1RXS J012256.6+072505	01 22 56.7	+07 25 09	0.818	7.34	0.0745
1RXS J033740.8+671904	03 37 40.5	+67 19 07	0.612	11.08	0.0745
1RXS J223616.6+452644	22 36 16.8	+45 26 44	0.776	9.55	0.289
1RXS J224441.6+175418	22 44 41.5	+17 54 18	0.796	9.59	0.795
1RXS J230043.2+772833	23 00 44.5	+77 28 38	0.599	11.29	0.0798
1RXS J233918.3–031038	23 39 18.3	–03 10 37	0.684	10.66	0.109

the Post- T Tauri stars (PTTSs) were fast rotators. Since young stars are fast rotators, their X-ray luminosities are about 2–3 orders of magnitudes above the X-ray luminosities of main-sequence stars of similar spectral type (Preibisch & Zinnecker 1999). Based on the realization that the X-ray selected samples are biased toward being fast rotators, Huélamo et al. (2004) suggested that late type stars with strong X-ray emission are the fastest rotators. So, we select young solar-type stars with X-ray emission as candidates of fast rotators.

Since 2004, we have been carrying out a long-term spectroscopic and CCD photometric survey of young late-type stars to search for new short-period WTTS and PTTS or young solar type stars. A similar work of ours on ROSAT selected WTTS in the Taurus-Auriga star formation regions has resulted in the discovery of 12 fast rotating WTTS (Xing et al. 2006). In the present paper, we will report the results of the photometric survey on another 16 young solar-type stars discovered from among strong X-ray sources.

This paper is organized as follows. The observations and data reduction are introduced in Section 2; the analysis and discussion are described and presented in Section 3. The conclusions are given in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

A group of bright stars with spectral type G were selected for photometric and spectroscopic observations. Here we present and discuss the photometry. A detailed discussion of the spectroscopic observations (obtained with the coudé spectrograph of the 2.16 m telescope of National Astronomical Observatories, Chinese Academy of Science (NAOC)) will be published later.

Our sample consists of 16 Northern ROSAT X-ray sources that have optical counterpart objects in the Tycho catalogue. It may be noted that the X-ray luminosities of both CTTSs and WTTSs typically span the range 10^{-4}–$10^{-3}L_{\rm bol}$ (Bertout 1989) and that nearly all stars including Upper Sco, Taurus-Auriga, Pleiades and Hyades stars are characterized by $\log(L_{\rm x}/L_{\rm bol}) \sim$ –3, as found by Preibisch & Zinnecker (1999). We selected those G-type stars that have high $L_{\rm x}/L_{\rm bol}$ ratios ($\log L_{\rm c}$+ 0.4 m_v $\geq$3.25) as candidate WTTSs or young solar-type G stars to our sample. The G spectral type of these stars was derived from the $B-V$ measurements given in the Tycho catalogue.

The basic data of the program stars are shown in Table 1. The observations were performed from October 2004 to February 2005 on the 60-cm Reflector equipped with a PI 1300×1340 photometric CCD camera. The plate-scale of the camera is $0''.46$ pixel^{-1}, providing a total field of view of $9'.93 \times 10'.24$. The standard Johnson B, V and R filters were used. In total, we obtained more than 200 CCD frames in each band for each star.

2.2 Data Reduction

Data reduction for all observation stars was carried out with the Image Reduction and Analysis Facility (IRAF) software. All the images were corrected for electronic bias and pixel-to-pixel gain variations (with sky flats). The relative magnitudes of the selected objects were obtained with the routines of the DAOPHOT package for crowded fields and with those of the APPHOT package for uncrowded fields. The differential photometry was done using the standard method. In each field, we analyzed the light-curves of several stars and selected those that do not vary over ten nights as our reference stars. The reference stars were examined for stability and we computed their averaged instrumental magnitudes as the magnitude of "artificial comparison". We did not transform our instrumental magnitudes to some standard system, since our main interest was to study the periodic light variations. The precision of the differential photometry for all the stars is better than 0.023 mag.

3 ANALYSIS AND DISCUSSION

The observed stars were checked for variability by comparing the mean standard deviation of each star's BVR measurements with the mean standard error of observations of the constant stars. Stars with mean standard deviations less than 1.5 time the standard error are regarded as showing no variability, and a period analysis was performed on the other stars regarded as variable. Nine of the 16 program stars were found to be variable. and their rotation periods were measured. The BVR light curves of these stars are displayed in Figure 1.

With the new photometric measurements, the rotation periods of nine stars were determined. The periods were computed using the Phase Dispersion Minimization (PDM) method (Lafler & Kinman 1965; Stellingwerf 1978) and checked with the Fourier analysis code PERIOD04 (Lenz & Breger 2005). In Table 2 we present the main results for the nine stars. The phase-folded light curves are shown in Figure 2.

Table 2 The Sample Stars of Our Observations

Objects	σ_v	ΔB (mag)	ΔV (mag)	ΔR (mag)	Periods (day)
1	2	3	4	5	6
1RXS J004005.0+501414	0.020	0.927	0.856	0.829	0.234 ± 0.001
1RXS J015627.3+122455	0.009	0.143	0.097	0.088	0.541 ± 0.001
1RXS J032548.0+365147	0.010	0.165	0.080	0.074	0.426 ± 0.001
1RXS J034628.3+242603	0.005	0.142	0.082	0.078	1.315 ± 0.002
1RXS J035201.9+243949	0.007	0.096	0.087	0.115	0.440 ± 0.002
1RXS J040009.4+081815	0.005	0.115	0.084	0.078	0.803 ± 0.001
1RXS J050425.7+040126	0.007	0.120	0.066	0.060	0.369 ± 0.002
1RXS J222007.2+493014	0.012	0.201	0.165	0.127	2.410 ± 0.003
1RXS J235810.1+673356	0.027	0.135	0.088	0.079	0.493 ± 0.001

The results of our present observations demonstrate that periodic light variation is not exceptional among active, solar-type field dwarfs. Nine such stars showed appreciable periodic light variations during our observation of 16 stars. The rotation periods of these stars are all shorter than 3 days. These periods and their amplitudes are similar to those of the solar-type members of the Pleiades cluster (Messina 2001a). However, the selection does not guarantee a "pure" TTS or young solar-type star sample, because other classes of stars, such as active binaries, share similar values of $L_{\rm x}/L_{\rm bol}$. Besides two eclipsing binaries (1RXS J004005.0+501411 and 1RXS J035201.9+243949), there are five ultra fast rotators ($P \leq$1.10 day) and two fast rotators ($P \geq$1.10 day) as defined in Messina et al. (2001b) among our program stars. We found that 1RXS J004005.0+501414 has a period of 0.2337 days, in good agreement with Hoffmann (1981), and that our period for 1RXS J035201.9+243949 has a period of 0.44 days, is in good agreement with Krishnamurthi et al. (1995). These results of the two binaries indicate that the light variation periods we obtained are reasonable and that the rotation periods of both binary systems have remained unchanged for many years.

In order to assess the significance level of the derived periods, we generated 10 000 synthetic light curves for each object using the Monte-Carlo method. The 10 000 random samples consist of normally-distributed random noise with maximum value the upper limit of the photometric error and have the same

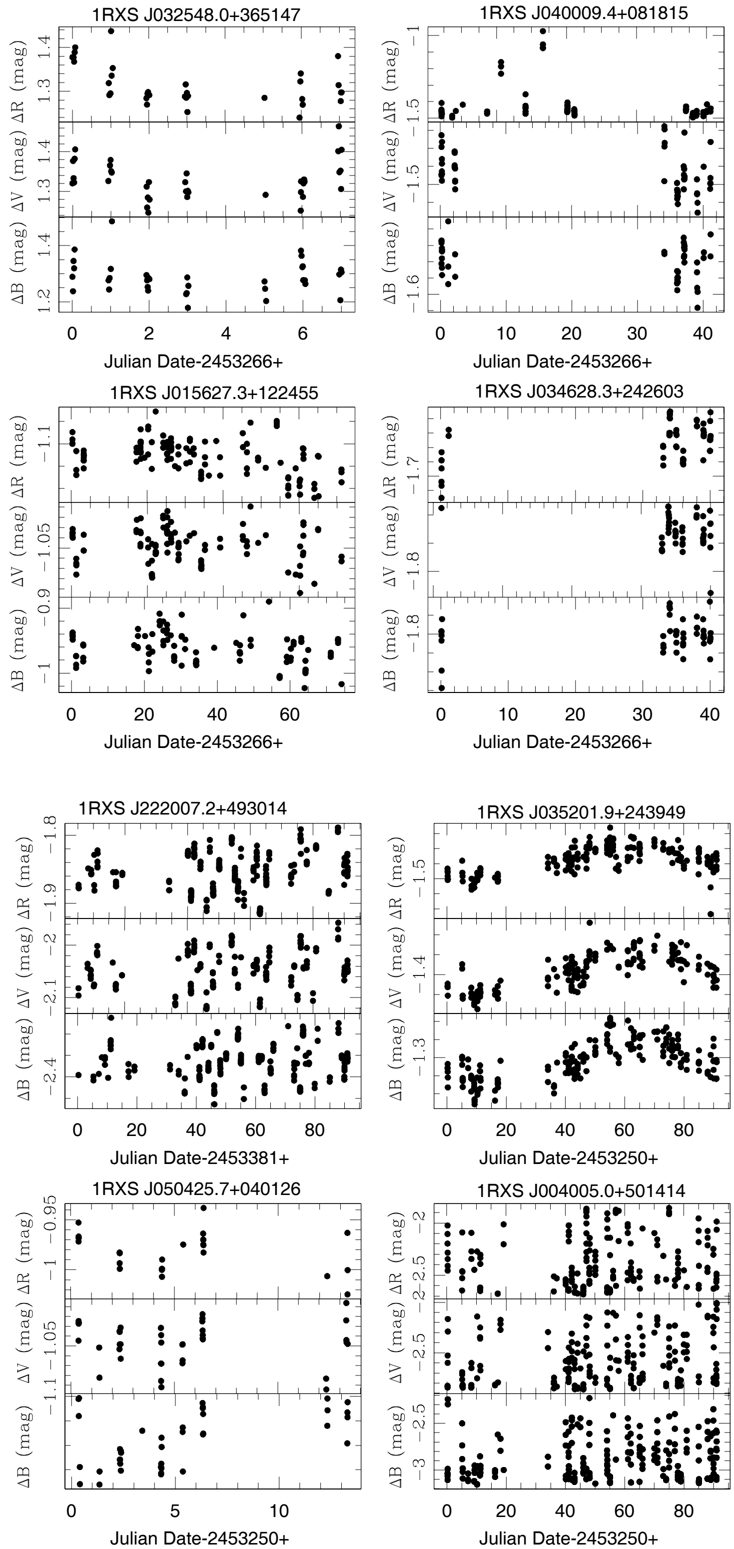

Fig. 1 BVR light curves of the observed WTTS candidates.

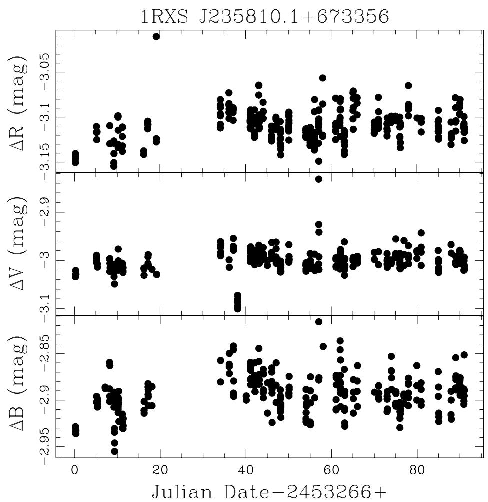

Fig. 1 Continued.

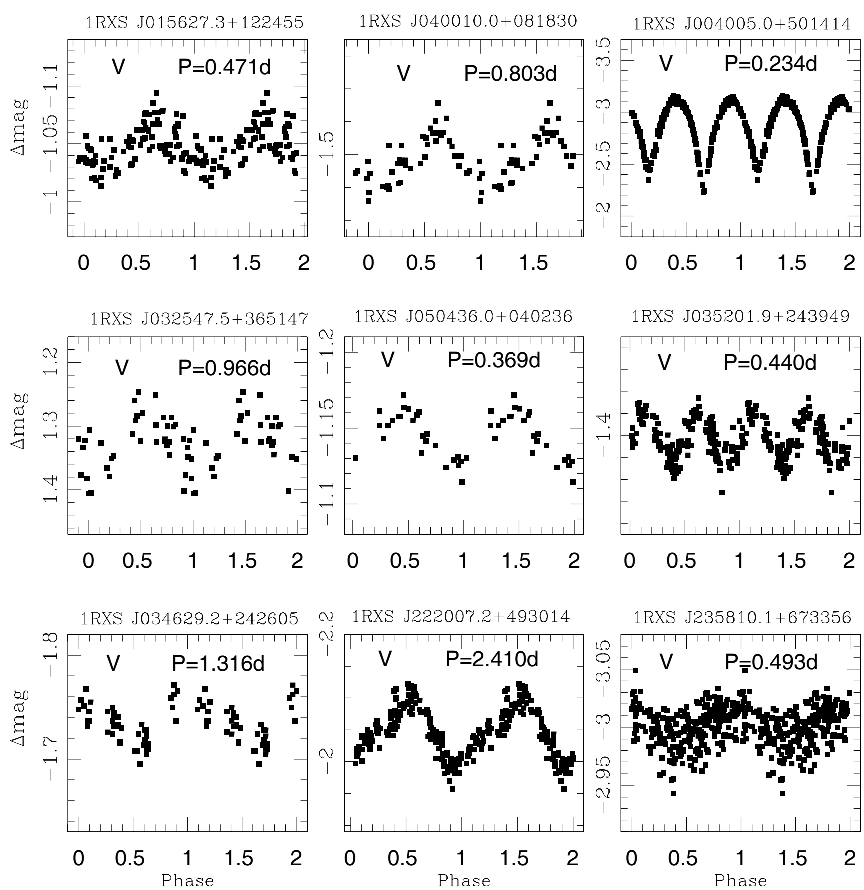

Fig. 2 Phase-folded light curves of nine WTTS candidates.

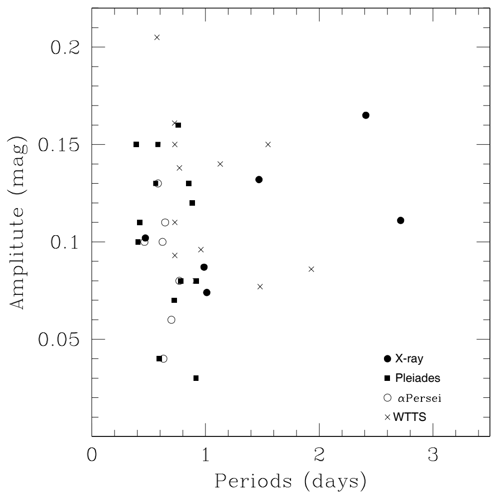

Fig. 3 Rotational periods versus V light-curve amplitude.

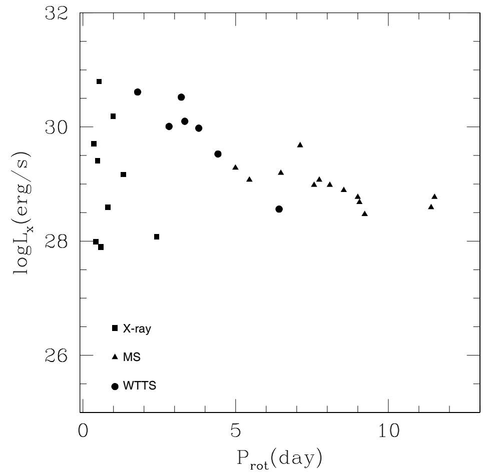

Fig. 4 Rotational period versus X-ray flux. Filled squares are the X-ray sources studied in this work, filled circles are the TTSs in the Lindroos study by Huélamo et al. (2004), and filled triangles are the dwarfs stars in the Pleiades and Hyades clusters from Hempelmann et al. (1995).

temporal sampling as our data (that is, we preserved the Julian Dates). We applied the PDM method to the 10 000 synthetic light curves and identified the period of each light curve with the peak in the periodogram (with the least $\Theta = s^2/\sigma_t^2$). Then we built the frequency distribution of the 10 000 periods, which can be used to indicate the probability that a peak of given height (a given period or frequency) may occur by chance in the periodogram. We therefore consider the period as secure only when the following three requirements are met: (1) The period is similar in all three bands B-, V- and R; (2) The comparison stars do not show any periodic variations; (3) The significance of the period is higher than 98%.

Our results appear to be consistent with the more comprehensive study of the angular momentum evolution assuming solid body rotation, e.g., Bouvier et al. (1997), in which the maximum rotational velocity decreases from $P \sim 0.5$ days (at $1M_\odot$, $1R_\odot$) at the age of Pleiades to (equatorial rotation) $P \sim 25.6$ days at the age of Sun. Since most of the PTTSs are fast rotators, the five ultra fast rotators in our sample should be PTTSs or reach ZAMS (Zero Age Main Sequence) stars, representing the very young solar-type stars that rotate rather rapidly. The two fast rotators should be Pleiades or Hyades age stars which representing young solar-type stars that rotate faster. The results of our observations are useful to investigate the initial angular momentum evolution of the Sun.

O'Dell et al. (1995) found main sequence stars that rotate very slow could have very low light variation amplitudes. In order to study weather the amplitudes of the photometric variability depend on the rotation periods of young solar type stars or not we have compiled from the literature data on PTTSs (Bouvier et al. 1997) and ZAMS clusters (Messina 2001a). In Figure 3 we plot the photometric amplitudes (ΔV) vs. rotational periods for our program stars and some PTTSs and ZAMS, in which no correlation is shown. This indicates that the total area of cool spots (on the star surface) do not depend on the rotational periods in our sample.

TTSs as a class, obey to the general relation between X-ray luminosity and rotation rate (Bouvier et al. 1985) for late-type active dwarfs. To check whether or not a rapidly rotating young solar type star or eclipsing binary has higher X-ray luminosities, we plot in Figure 4 the rotational periods versus the X-ray luminosity (logLx) for the sample stars, the TTSs in Lindroos systems (Huélamo 2004), and the young main sequence stars in the Pleiades and Hyades clusters. As shown, for TTS and main sequence stars, the faster rotators tend to have higher X-ray luminosities. However, no correlation between the X-ray luminosity and rotation periods is detected for our sample stars that rotate ultra fast.

4 CONCLUSIONS

We have presented the photometric monitoring results of 16 X-ray selected young solar type stars. Nine of these stars show periodical variabilities. Based on the new measurements, the rotational periods of these nine variables are determined: the range from 0.234 to 2.410 days. These results provide further evidence for enhanced angular velocities in PMS stars approaching the ZAMS on their radiative tracks as predicted by models of angular momentum evolution of pre-main sequence stars. We conclude that a substantial fraction of solar-type dwarfs with periods of several days shows light variation with amplitudes of the order of 1–2 percent.

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References

Bertout C., 1989, APA&A, 27, 351
Bouvier J., Bertout C., Benz W. et al., 1985, in "Nearby Molcular Clouds" Lecture Notes in Physics, G. Serra ed., p.222
Bouvier J., Cabrit S., Fernandez M. et al., 1993, A&A, 272, 176
Bouvier J., Covino E., Kovo O. et al., 1995, A&A, 299, 89
Bouvier J., Wichmann R., Grankin K. et al., 1997, A&A, 318, 495
Grankin K. N., Ibragimov M. A., Kondrat'ev V. B., 1995, Astron. Zh., 72, 894
Hempelmann A., Schmitt J. H. M. M., Schultz M., 1995, A&A, 294, 515
Herbig G.H., 1962, Advances in A&A, 1, 47
Herbst W., Herbst D. K., Grossman E. J. et al., 1994, AJ, 108, 1906
Herbst W., Rhode K. L., Hillenbrand L. A. et al., 2000, AJ, 119, 261
Hoffmann M., 1981, IBVS, 1976
Huelamo N., Fernández M., Neuháuser R. et al., 2004, A&A, 428, 953
Joy Alfred H., 1945, ApJ, 102, 168
Krishnamurthi A., Terndrup D. M., Pinsonneault M. H. et al., 1998, ApJ, 493, 914
Lafler J., Kinman T. D., 1965, ApJS, 11, 216
Lawson Warrick A., Crause Lisa A., Mamajek Eric E. et al., 2001, MNRAS, 321, 57
Lenz P., Breger M., 2005, CoAst, 146, 53
Messina S., 2001, A&A, 371, 1024
Messina S., Rodonó M., Guinan E. F., 2001, A&A, 366, 215
O'Dell M. A., Panagi P., Hendry M. A. et al., 1995, A&A, 294, 715
Preibisch T., Zinnecker H., 1999, AJ, 117, 2381
Prosser C. F., Shetrone M. D., Dasgupta A. et al., 1995, PASP, 107, 211
Shevchenko V. S., Herbst H., 1998, AJ, 116, 1419
Stellingwerf R.F., 1978, ApJ, 224, 953
Wichmann R., Bouvier J., Allain S. et al., 1998, A&A, 330, 521
Xing L. F., Zhang X. B., Wei J. Y., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 716