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ROSAT OBSERVATIONS OF STAR FORMING REGIONS [1]

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RESUMEN

Las observaciones en rayos X obtenidas con satélites de regiones de formación estelar, han proporcionado información nueva sobre los procesos de formación estelar. En este trabajo resumimos los resultados principales obtenidos inicialmente con el satélite *Einstein* y posteriormente presentamos los nuevos resultados obtenidos por el satélite alemán de rayos X, *ROSAT*. Aunque la evaluación de los datos *ROSAT* no está terminada aún, los proyectos *ROSAT* han proporcionado algunos resultados nuevos y muy interesantes que serán discutidos aquí.

ABSTRACT

X-ray observations of star forming regions carried out by satellite observatories have provided us with new insights into the process of star formation. Here we summarize the main results obtained by the pioneering work with the *Einstein* satellite, followed by a presentation of new achievements by *ROSAT*, the German X-ray satellite. Although the evaluation of the *ROSAT* data is not completed yet, the ongoing *ROSAT* projects already have yielded some very interesting and new results which will be discussed here.

Key words: **STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

X-ray observations of star forming regions (SFR) have turned out to be a very powerful tool for the study of the star formation process. X-ray studies of pre-main sequence (PMS) stars, which were found to be an important constituent of the soft X-ray sky, have significant implications for our understanding of these objects, in particular of the T Tauri stars, which are low-mass ($M \leq 3M_\odot$) PMS stars. The pioneering work in the field of X-ray observations of PMS stars was done as for many other types of objects by the *Einstein* satellite, the first imaging X-ray observatory, which was launched at the end of 1978. While *EXOSAT*, the next X-ray satellite with an imaging telescope, had only little influence in the field of star formation, a big impact, leading to a major step forward in our understanding of the star formation process came from *ROSAT*, the German X-ray satellite launched in 1990. The all-sky survey carried out by *ROSAT* (the first one with an imaging telescope in the soft X-ray range) allows for the first time the construction of large, *unbiased* samples of various classes of X-ray sources. Moreover, the performance (sensitivity and angular resolution) of the *ROSAT* telescope/detector system is quite superior to the corresponding *Einstein* systems.

Following we shall first give an overview of the main results achieved by the *Einstein* observatory and their implications for our understanding of the star formation process; then the new achievements by *ROSAT* will be

[1]Based on observations collected at the European Southern Observatory at La Silla, Chile, at the Calar Alto Observatory (Centro Astronómico Hispano-Alemán), Almería, Spain, and at the Lowell Observatory, Flagstaff.

presented. However, while 13 years after the end of the *Einstein* mission, most of the data have been actually analyzed and published, the situation is quite different for the data obtained with *ROSAT*. Now, *ROSAT* is still gathering data, and most of the X-ray data of star forming regions obtained with *ROSAT* require extensive follow-up observations in other wavelength ranges. Hence, essentially all *ROSAT* projects dealing with star formation are in some kind of intermediate state, and only little has been published. Here we present ongoing *ROSAT* projects and discuss the results obtained so far. Special emphasis will be given to results obtained by our group from the *ROSAT* all-sky survey.

2. *EINSTEIN*: THE PIONEERING WORK

In the seventies several predictions of X-rays from PMS stars based on different physical mechanisms were made. Thermal X-rays from a 10^6 K solar-like corona were predicted by Bisvonatyi-Kogan & Lamzin (1977). The discovery of very strong emission lines produced in 10^5 K gas by *IUE* (Gahm et al. 1979) encouraged the suggestion of X-ray emitting regions further out in T Tauri winds. Mundt (1981) proposed the production of X-rays at the surface of YY Ori stars due to an accretion shock, as there is spectroscopic evidence for infalling gas in this subclass of T Tauri stars. However, prior to 1978 essentially no observational evidence was found for X-ray radiation from PMS stars. Only indirect observational indications for X-ray radiation from T Tauri stars were found by the observation of extended X-ray emission in the Orion SFR by the *ANS* satellite (den Boggende et al. 1978).

The *Einstein* observatory results on PMS stars have been extensively described in several review papers (e.g. Feigelson 1987; Montmerle & André, 1988; Walter 1990); here we want to summarize the main results of these observations:

- The X-ray luminosities of PMS stars are on the average higher by a factor of 10^2–10^4 than those of main-sequence stars of the same spectral type. From the analysis of the spectral energy distribution it has been shown that the physical mechanism for the emission of the X-rays is thermal emission from an optically thin, solar-like coronal plasma with a temperature of about 10^7 K.

- Time-dependent repeated observations in the ρ Oph cloud by Montmerle et al. (1983) showed that strong X-ray variability is widespread in X-ray emitting PMS stars, making star forming regions look like 'Christmas-trees' in X-rays. A possible explanation might be that the X-ray emission is related to solar-type magnetic activity causing flares which are more powerful than solar flares by a factor of 10^3 to 10^4. However, it is still an open question whether the total X-ray activity in PMS stars is due to flare events. For several stars [e.g., DG Tau (Feigelson & DeCampli 1981) or AS 205 (Walter & Kuhi 1984)] individual flare events could be established.

- Typically about one third of all known T Tauri stars were detected in a single exposure. Walter & Kuhi (1981) found for the T Tauri stars in Taurus-Auriga an anti-correlation between the X-ray flux and the equivalent width of Hα and suggested that the coronal X-ray emission should be efficiently absorbed in the circumstellar environment. However, this anti-correlation has been highly controversial, since it was neither found by Montmerle et al. (1983) for the ρ Ophiuchi dark cloud nor for Chamaeleon by Feigelson & Kriss (1989). Moreover, due to the already mentioned variability of the X-ray flux, different T Tauri stars showed up on different X-ray exposures in the Taurus-Auriga cloud. The anti-correlation found by Walter & Kuhi also contrasts strongly with the good Hα vs. X-ray correlation found for active late-type stars (cf. e.g., Montmerle & André 1988).

- Probably the most important result of *Einstein* observations of star forming regions was that they revealed the existence of a new population of PMS stars. Spectroscopic and photometric observations of the optical counterparts of 5 serendipitious sources in the Taurus-Auriga SFR by Feigelson & Kriss (1981) and Walter & Kuhi (1981) showed that these stars had a late type spectrum K7–M0, were located above the main sequence, had weak Hα emission with equivalent widths between 2 and 5 A, and had strongly enhanced Li I λ6707 absorption. This absorption line is a stringent indicator for a very low age, since Li is very rapidly depleted during the main-sequence phase by proton-capture reactions (e.g., Bodenheimer 1965). Consequently these objects were identified as low-mass PMS stars.

3. THE TWO CLASSES OF LOW-MASS PMS STARS: CTTS VS. WTTS

The objects found in the *Einstein* observations contrast in some fundamental properties with the traditional picture of the T Tauri stars as have emerged since the original discovery by Joy (1942). T Tauri stars, whose physical nature as PMS stars was first recognized by Ambartsumian (1947), were classified on the basis of their morphological, photometric, and spectroscopic properties. According to the classical definition by Herbig (1962), T Tauri stars are irregular variables with a strong chromospheric emission line spectrum with Balmer lines and Ca II H and K being most conspicuous. Indeed, in the optical spectral range, T Tauri stars were usually identified on the basis of their strong Hα (EW$_{H\alpha} \geq$ 10 A) emission. Another characteristic property of the T Tauri stars (first detected by Eugenio Mendoza (1966, 1968)) is a strong infrared (IR) excess. The IR luminosity can exceed the optical luminosity by a large factor. Consequently, quite a number of T Tauri stars (in particular embedded sources) were found by IR surveys of dark clouds. The observational properties strongly supported the general belief that all T Tauri stars were associated with dense circumstellar matter.

The new class of PMS stars discovered as X-ray sources lack both strong emission lines and the IR excess, which is interpreted as due to the absence of dense circumstellar matter. Accordingly these objects were called 'naked' or weak-line T Tauri (WTTS) stars, the latter term now being commonly used, while the objects with strong emission lines were denoted 'classical' T Tauri stars (CTTS). In Table 1 we summarize the main differences between the CTTS and the WTTS.

Table 1. Synopsis of Main (Contrasting) Properties of CTTS and WTTS

	CTTS	WTTS
Detection	Optical/IR	X-rays
EW$_{H\alpha}$	$>$ 10 A	$\leq$ 10 A
IR excess (2.2μ)	$>$ 0.1 mag	$\leq$ 0.1 mag
UV excess, veiling	yes	no
Dense circumstellar matter	yes	no
$\dot{M}_{wind}$	10^{-9}–10^{-7} $M_\odot$/yr	$\leq 10^{-9}$ $M_\odot$/yr

We want to note, however, that the distinction between the CTTS and the WTTS is in part somewhat arbitrary, since there is a smooth transition between both classes. Moreover, due to the pronounced photometric and spectral variability exhibited by many PMS stars, there are cases which show alternately CTTS or WTTS characteristics. As an especially striking example we refer to T Cha which can change its character from one night to the next; Hα, for instance, changes within two nights from a P Cygni type profile with an absorption component (EW $\sim$ 4 A) well below the continuum level and a very weak emission component to a strong emission with an equivalent width of 62 A (Alcalá et al. 1993; Alcalá et al. in preparation).

For several reasons WTTS turned out to be a very important constituent of star forming regions:

- WTTS are much more numerous than CTTS. They are of crucial importance for any construction of the Initial Mass Function and for a determination of the star formation efficiency. But, since with the *Einstein* observatory only small parts of the individual star forming regions could actually be observed, the exact ratio of WTTS/CTTS is unknown. For the Tau-Aur cloud Walter et al. (1988) stated that the WTTS would outnumber the CTTS by a factor of 10:1. However, because only 20% of the Tau-Aur cloud was actually observed in X-rays, this result is based on an extrapolation and has to be verified by a spatially complete sample. For other star forming regions e.g., Chamaeleon much lower ratios of WTTS/CTTS were found (Feigelson & Kriss 1989). It should be noted that all *Einstein* results were obtained in the central parts of the star forming regions where all the CTTS are found; no surrounding areas were studied.
- As the location of the WTTS in the H-R diagram shows, the WTTS represent only in part the older (up to several 10^7 years), more evolved population of the T Tauri stars, the post-T Tauri stars (Herbig 1978). Many of them are located in exactly the same region of the H-R diagram as the CTTS, which implies the same age of about 10^6 years for both groups. This could be due to a faster development of these WTTS, i.e., they may have lost their dense circumstellar matter earlier than the corresponding CTTS. On the other hand, it cannot be excluded that some WTTS never had circumstellar matter as dense as found for the CTTS. A clarification of this question is important for any modelling of the star formation process.
- Due to the lack of a significant amount of circumstellar matter, WTTS offer much better observational possibilities than the CTTS to study the properties of the stars themselves. In CTTS we observe primarily not a star, but the interaction of the star with a dominant circumstellar environment.

4. THE *ROSAT* SATELLITE

A major step forward in the X-ray observations of star forming regions was achieved with the launch of the German X-ray satellite '*ROSAT*'. With this satellite the above mentioned drawbacks of the *Einstein* observations were at least in part overcome; for a more detailed description of *ROSAT* and its detectors we refer to Trümper (1983) and Pfeffermann et al. (1986). The *ROSAT* all-sky survey was carried out after the commissioning and calibration phase for a duration of six months, using the Position Sensitive Proportional Counter (PSPC). Its mean limiting flux of about 2×10^{-13} erg s^{-1} cm^{-2} (in regions of deeper exposures at high ecliptical latitudes considerably fainter flux limits have been achieved) corresponds roughly to the sensitivity of typical pointed *Einstein* observations. Pointed *ROSAT* PSPC observations allow to achieve a limiting flux one order of magnitude below corresponding *Einstein* IPC observations. This is demonstrated by Figure 1 which shows the X-ray luminosities of T Tauri stars in Chamaeleon obtained from pointed *Einstein* IPC observations (Feigelson & Kriss 1988), from the *ROSAT* all-sky survey, and from pointed *ROSAT* PSPC observations (Braun 1992; Zinnecker et al. in preparation). Exposure times for the pointed observations were 7.6 ksec and 32.5 ksec for the *Einstein* and *ROSAT* images, respectively.

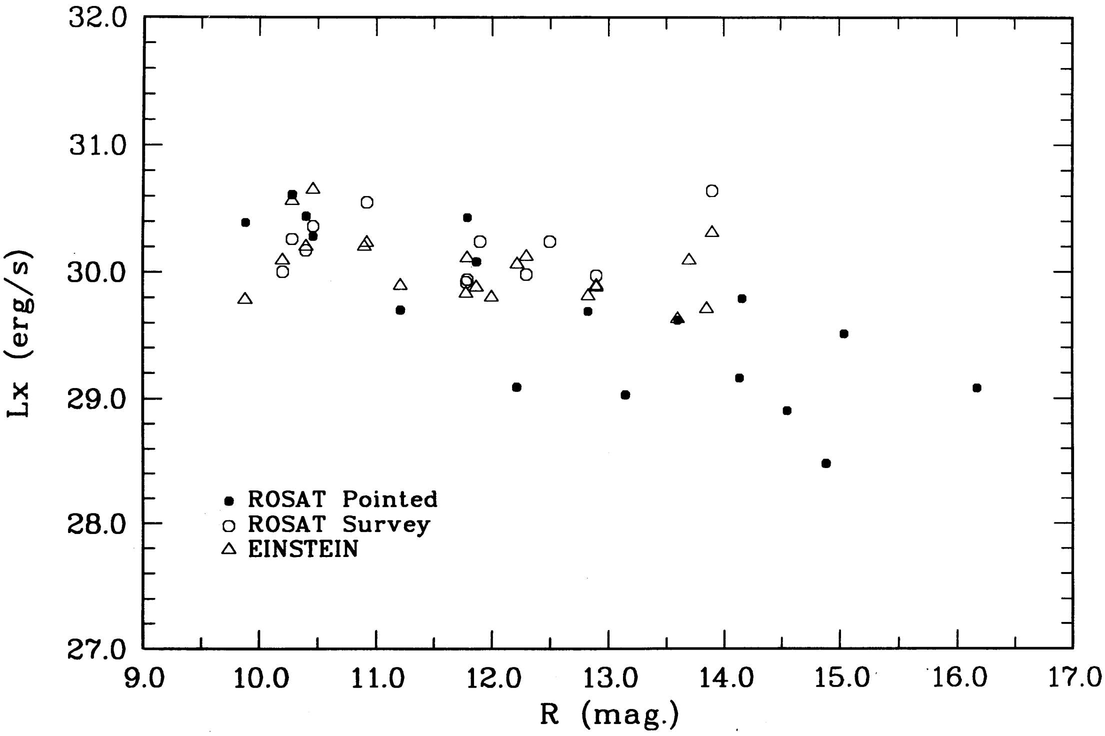

Fig. 1. X-ray luminosities of known T Tauri stars in Chamaeleon. Triangles: *Einstein* IPC observations, circles: *ROSAT* all-sky survey, dots: pointed *ROSAT* observations.

The superior angular resolution of the *ROSAT* PSPC (which exceeds that one of the *Einstein* IPC by at least a factor of three), is quite important for observations of star forming regions. Pointed *ROSAT* PSPC observations in the Chameleon dark cloud by Feigelson et al. (1993) revealed that part of the *Einstein* IPC sources found by Feigelson & Kriss (1989) are indeed double or multiple sources. As the most striking example, the *Einstein* source CHX 15, which shows a somewhat elongated structure (cf. Figure 1 in Feigelson & Kriss) could be resolved into the five *ROSAT* sources CHXR 35, 37 40, 41, and 46 (cf. Figure 2b in Feigelson et al.). Other examples are CHX 9 which may include CHXR 23, 27, and 29 or CHX 16 which could be resolved into CHXR 42, 44, and 45. This shows that with the modest angular resolution of the *Einstein* IPC images the number of X-ray sources was significantly underestimated, or consequently, the X-ray luminosity of the individual sources overestimated. As Feigelson et al. remark, this fact has to be taken into account when comparing global *Einstein* and *ROSAT* results. In addition, for a direct comparison also the somewhat different spectral bands of *Einstein* (0.2–4 keV) and *ROSAT* (0.1–2.4 keV) have to be taken into account.

5. THE DATA BASE

The star forming regions in Taurus-Auriga, Orion, Chamaeleon, and Lupus have been chosen for a detailed study, because all four have been extensively studied in the optical and IR wavelength regimes. In particular, the vast majority of the CTTS known in these regions are quite well studied. Differences in the properties of the CTTS between the four clouds have been found; the CTTS in Lupus are outstanding, since as shown by Krautter & Kelemen (1987) their average mass is significantly lower than that found for any other T Tauri association. The SFRs in Tau-Aur, Cha, and Lupus are roughly at the same distance of about 150 pc; the Orion SFR is about three times as distant.

Since we expect WTTS to occupy a larger area on the sky than the CTTS, we also chose for our investigation areas which border on the regions with CTTS, but in which no CTTS were found. Table 2 gives an overview of the limits of our study fields and the numbers of X-ray sources found in the all-sky survey. The effective exposure times differ from cloud to cloud; they are in the range of 400–600 seconds for the Orion SFR, of 200–500 for Taurus-Auriga, 700–1 000 seconds for Chamaeleon, and 300–450 for the Lupus SFR.

Table 2. Limits of Study Areas and Number of X-ray Sources

Region	α_{min}	α_{max}	δ_{min}	δ_{max}	N
	(2000)		(2000)		
Orion	5.0	6.0	–14.0	16.0	820
Tau-Auriga	4.0	5.0	15.0	34.0	689
Chamaeleon	8.7	14.0	–85.0	–74.0	230
Lupus	15.1	16.4	–47.0	–32.0	531

The area covered in Orion includes the molecular clouds complexes A and B described by Maddalena et al. (1986) and the λ Orionis reg as well. The area covered in Chamaeleon includes both Chamaeleon I and Chamaeleon II clouds, that one in Lupus includes the Lupus 1–4 subclouds (e.g., Krautter 1991).

In addition to the survey data we obtained data from pointed observations in the Taurus-Auriga, Chamaeleon and Lupus SFRs. In Tau-Aur and Chamaeleon long exposures of individual areas were obtained, whereas in Lupus the central parts including the Lupus 1–3 subclouds were observed in a raster scan with a total of 66 individual pointings. The above mentioned pointing in Chamaeleon (Braun 1992; Zinnecker et al. in preparation) with an exposure time of 32.5 ksec is centered on nearly the same position as one of Feigelson et al.'s (1993) two pointings in Chamaeleon with an exposure time of $\sim$ 6.0 ksec each.

5.1. Optical Identification of X-ray Sources

As a first step in order to identify the optical counterparts of the X-ray sources in our study fields we searched for positional coincidences with existing catalogues, in particular with the SIMBAD data base of the Centre de Données Astronomiques in Strasbourg. The criterium for accepting a SIMBAD source as the optical counterpart was that the SIMBAD position was within a circle of 60 arc sec around the X-ray position. This was the case for about 30% of the X-ray sources (20% are within a circle of 40 arcsec). These sources correspond to HR, HD or SAO stars, CTTS and few WTTS known from previous *Einstein* observations. However, about a quarter of the stellar Simbad counterparts had to be included in the spectroscopic identification programme described below, since only insufficient information is available.

A pre-selection could be obtained from the known relations of the X-ray luminosity F_x vs. the optical luminosity F_V. Since one does not expect any stellar counterpart fainter than 17th magnitude, only objects brighter than that limit were actually observed. Also excluded were very soft sources, since it is known that WTTS do not have soft spectra. However, since —because of the low count rates— spectral information was available only in exceptional cases from our survey sources, only the broad-band hardness ratios

$$\mathrm{HR1} = (F_{0.5-2keV} - F_{0.1-0.4keV})/(F_{0.5-2keV} + F_{0.1-0.4keV})$$

and

$$\mathrm{HR2} = (F_{0.9-2keV} - F_{0.5-0.9keV})/(F_{0.9-2keV} + F_{0.5-0.9keV})$$

could be used. (A more detailed discussion of the broad-band properties of WTTS and CTTS can be found in § 7).

Typically 2–3 candidates in the X-ray error box fulfilled the above criteria. The final optical identification was obtained on the basis of spectroscopic observations. The most important criterion for the PMS nature of a stellar counterpart was the presence of the Li I λ 6707.7 absorption line. In addition to the Li criterion, we used the presence of the Hα emission line as chromospherical activity indicator. We would like to note that the presence of Hα emission is not necessarily a PMS indicator, since dMe stars show chromospheric emission lines like Hα, but are definitely not PMS stars. Subsequent photometric observations of the newly discovered WTTS (and of a few CTTS) in the optical and IR spectral ranges were already carried out or wil be carried out in the near future. Observations were carried out at various telescopes at the European Southern Observatory at La Silla, the Calar Alto observatory of the Max-Planck-Institut für Astronomie, and at the Perkins telescope of the Ohio State University at the Lowell Observatory in Flagstaff.

6. COLLECTIVE PROPERTIES OF STAR FORMING REGIONS

6.1. Number of WTTS vs. CTTS

Table 3 presents the number of WTTS and CTTS in the Taurus-Auriga, Orion, Chamaeleon, and Lupus star forming regions which were studied in detail by us. The numbers of CTTS were taken from the literature, the WTTS include our own new identifications, which are mainly based on the *ROSAT* all-sky survey data, as well as WTTS published in the literature.

Table 3. Number of WTTS and CTTS in the SFRs Studied

Star forming region	WTTS	CTTS	WTTS/CTTS
Taurus-Auriga	95	74	1.3
Orion	150	100	1.5
Chamaeleon	99	70	1.4
Lupus	132	54	2.4

From these numbers it is clear that the WTTS outnumber the CTTS by at least a factor of 1.5–2.5. However, since no correction factor for completeness has yet been applied, the ratios given here are strict lower limits only. The real ratios will be higher and ratios as high as 10:1 as suggested by Walter et al. (1988) can certainly not be excluded.

6.2. Comparison Survey: Deep Pointed Observation in Chamaeleon

In the deep pointed observation of 32.5 ksec in the southern part of the Chamaeleon I dark cloud 54 X-ray sources were detected, while in the survey only six sources had been found in the same area. Of these 54 X-ray sources, 29 could be identified with known PMS (CTTS or WTTS) stars. In addition, spectroscopic observations of 17 X-ray sources revealed 15 new WTTS (and 2 dMe stars). 8 X-ray sources have only very faint stars within the error box; they could be embedded sources, but they are too faint to be observed with a 1.5-m telescope. Clearly, already the available data show that the *ROSAT* all-sky survey data are rather incomplete in the investigated regions. Whether this holds for this specific dark cloud area only or for the whole Chamaeleon region, cannot be decided yet. A comparison of survey data in pointed observations in Tau-Aur by Neuhäuser et al. (1994) reveals a much higher completeness of the survey data. On the other hand, there is evidence that the 32.5 ksec exposure covers indeed already the low-luminosity sources of the X-ray luminosity function, since the number of X-ray sources increases only by about a factor of 1.5 as compared with the 34 sources detected by Feigelson et al.'s (1993) in their 6 ksec exposure in the same area. The X-ray sources of both pointed observations are presented in Figure 2.

6.3. Spatial Distribution

Figure 3 shows the spatial distribution of the PMS stars in the Chamaeleon star forming area. Open circles denote WTTS, dots CTTS. It is immediately evident that the WTTS are distributed over much larger areas

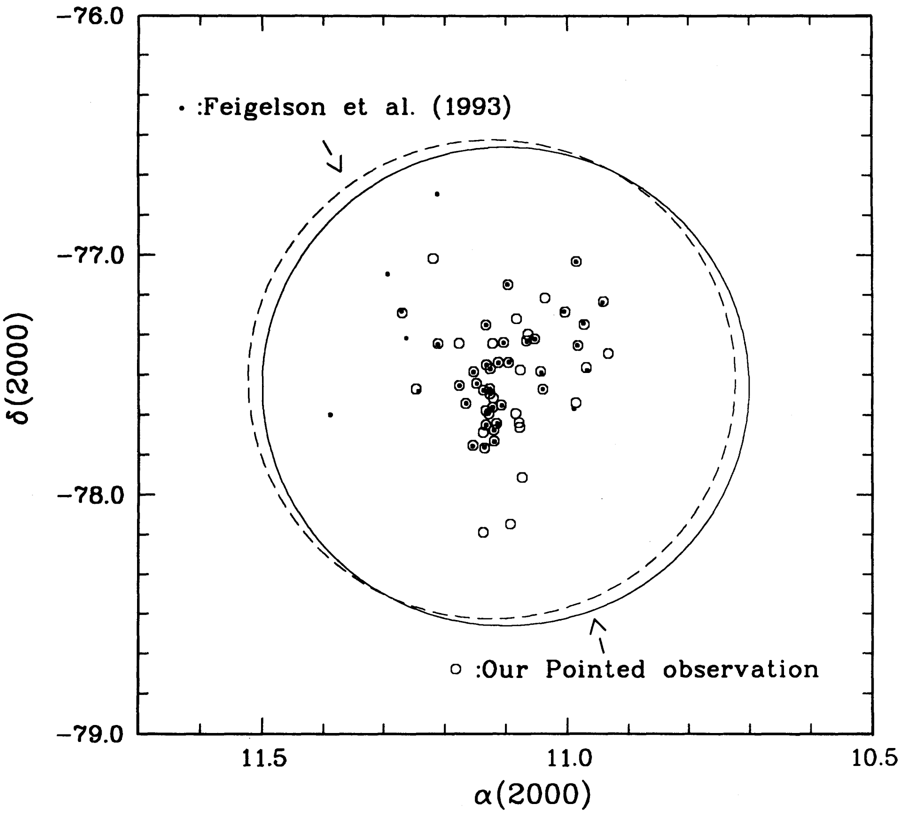

Fig. 2. X-ray sources in pointed observations of Chamaeleon I. Circles denote our own data, dots those from Feigelson et al. (1993)

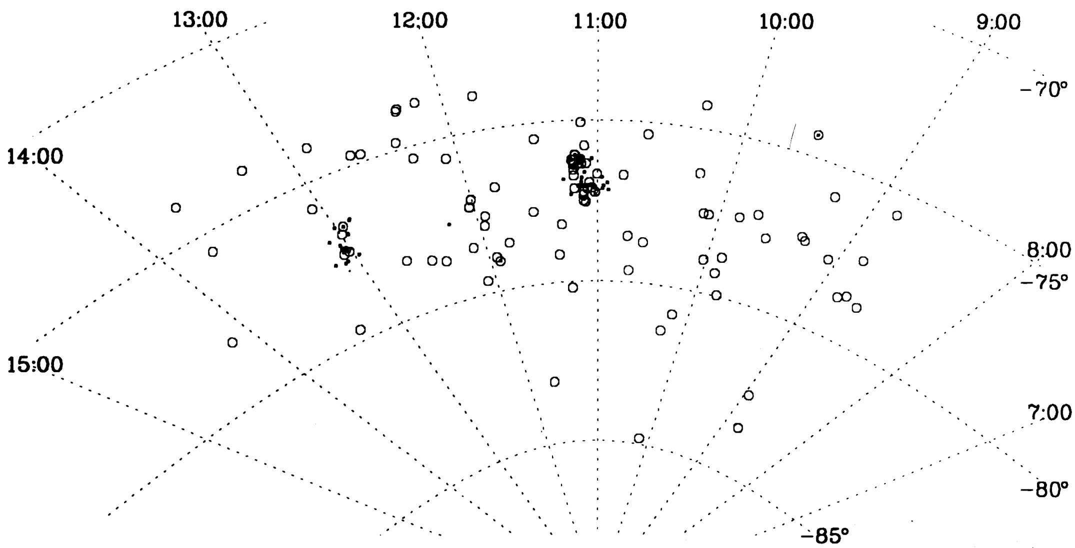

Fig. 3. Spatial distribution of PMS stars in Chamaeleon. Circles denote WTTS, dots CTTS.

than the CTTS which are concentrated towards the densest parts of the dark clouds, which correspond for example in the case of the Chamaeleon area to the 'classical' Cha I ($\sim 11^h, -77^o$) and Cha II ($\sim 13^h, -77^o$) star forming regions (e.g., Schwarz 1991). However, WTTS are also found far away from the cloud cores containing the CTTS. We found the same spatial structure of CTTS and WTTS in the Orion, the Tau-Aur and the Lupus dark cloud regions, too.

The spatial distribution clearly shows that the WTTS can give information on the star formation history. Walter (1988) suspected that the distance of the WTTS to the cloud cores should be correlated with the age. As a crucial test the WTTS which are far away from the cloud cores should be closer to the main sequence in the H-R diagram than those found in the vicinity of the cloud cores. Unfortunately, from our sample we are not yet able to do this, since for part of the objects identified spectroscopically as WTTS we still do not know the luminosity because of missing optical and/or IR photometry.

The borders of the study area shown in Figure 3 are rather arbitrary; they represent the field borders chosen by us originally when defining our X-ray samples. Within the limits presented here we do not see a significant decrease of the number density of WTTS with increasing distance from the cloud cores. Of course, as studies of *ROSAT* all-sky survey fields at high galactic latitudes show, the number density of WTTS in those fields far away from dark cloud complexes is indeed very low, even if WTTS or also CTTS are found at high galactic latitudes far away from any dark cloud area (e.g., Ruczinski & Krautter 1983; Pallavicini et al. 1992). It would be very interesting to investigate where the number density of WTTS actually decreases. Since the observational effort for such a project will be rather demanding, only one of the smaller star forming regions like Chamaeleon would be suitable for a complete study. Alternatively, selected strips extending radially from the cloud cores could be chosen.

7. PHYSICAL PROPERTIES OF PMS X-RAY SOURCES

7.1. Distribution of Spectral Types

Figure 4 shows the distribution of spectral types in Orion, Lupus and Chamaeleon for both WTTS and CTTS. The distribution of the latter has been taken from Krautter & Kelemen (1987) for Chamaeleon and Lupus, and from Herbig & Bell (1988) for Orion. It is immediately obvious that in all three SFR there are

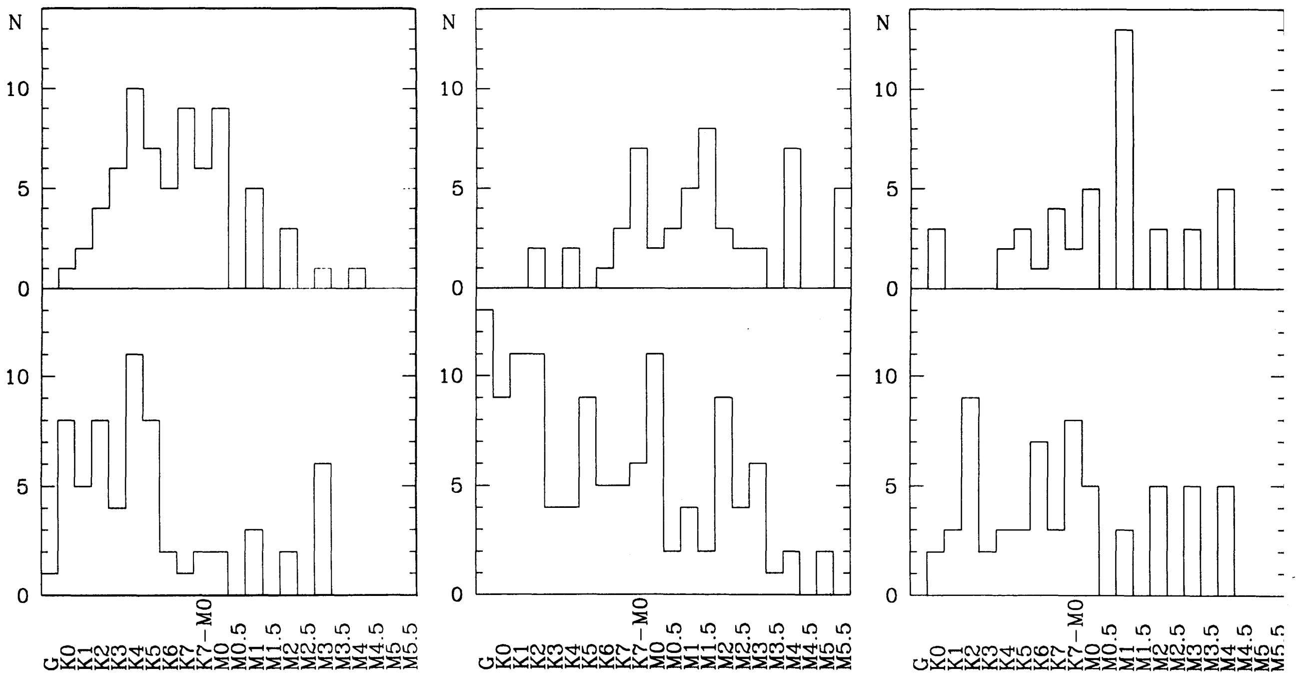

Fig. 4. Distribution of spectral types of CTTS (upper panel) and WTTS (lower panel) in Orion (left), Lupus (middle) and Chamaeleon (right).

nany more WTTS than CTTS with spectral types earlier than K2. For the late M type stars the situation is ess clear: Whereas in Chamaeleon about as many WTTS as CTTS are found, there are many fewer WTTS in Lupus and Orion. Whether this is real or caused by a selection effect cannot be decided yet. However, the fact hat this effect is most pronounced in Orion where, because of the larger distance, the limiting X-ray luminosity s about ten times higher than in Lupus and Chameleon, strongly suggests a selection effect at least for Orion. A selection effect might also be present in Lupus, since for this SFR the survey data are of relatively low quality because of high background radiation. The analysis of pointed observations in Lupus which has just started night clarify this question.

Selection effects can be excluded for the stars with earlier spectral types. As a comparison with the evolutionary tracks for the PMS evolution by D'Antona & Mazzitelli (1994) shows, this sub-sample of the WTTS represents on one hand the older PMS stars which have already moved closer to the main seqence. On the other hand, most stars in this sub-sample also have masses $M \geq M_{\odot}$, and they are much more numerous than corresponding CTTS. This could be interpreted in terms of a faster evolution, i.e., PMS stars with higher nasses lose their circumstellar environment earlier than stars with lower masses.

The character of the Hα line in WTTS depends on the spectral type. As an example in Figure 5 we show the distribution of spectral types of WTTS in Lupus for stars with Hα in emission and for stars where Hα is n absorption with some emission filled in. With the exception of two objects there are no WTTS with filled-in Hα absorption and spectral types later than K2. This behavior can easily be understood in terms of a changing relative contribution of the emission and photospheric absorption components. For increasing photospheric temperatures the strength of the photospheric absorption component increases, whereas the flux of the emission component remains roughly constant. Hence, the earlier the spectral type, the larger is the relative contribution of the absorption component.

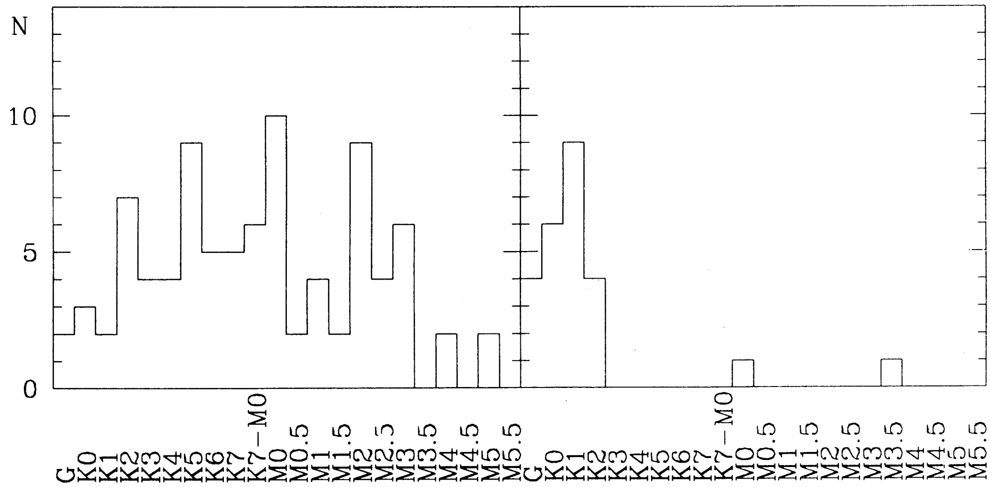

Fig. 5. Distribution of spectral types of WTTS in Lupus for stars with Hα in emission (left side) and for stars where Hα is in absorption with some emission filled in (right side).

7.2. Difference of Hardness Ratios between WTTS and CTTS

Figure 6 exhibits the hardness ratios HR1 vs. HR2 for the WTTS and CTTS in the Lupus-3 subcloud. (The definition of the *ROSAT* hardness ratios has been given in § 5). It is obvious that the CTTS have on the average harder spectra than the WTTS, in particular with respect to HR1. However, it is also clear that no real soft sources are found among the WTTS. A similar result has been found by us for Chamaeleon and by Neuhäuser et al. (1994) for the Tau-Aur, Per, and Sco-Cen star forming regions. The difference between the mean hardness ratios of WTTS and CTTS corresponds to a difference of about a factor of ten in hydrogen column density towards the sources. For objects of essentially the same distance this can hardly be explained by density variations in the ISM, and thus the interstellar absorption cannot be the main reason for the significantly different hardness ratios. Since the differences in hardness ratio are about the same for PMS stars in different SFR, different intercloud absorption can also be excluded. It seems safe to conclude that the harder spectrum of the CTTS is caused by the higher absorption due to the dense circumstellar matter connected with the CTTS.

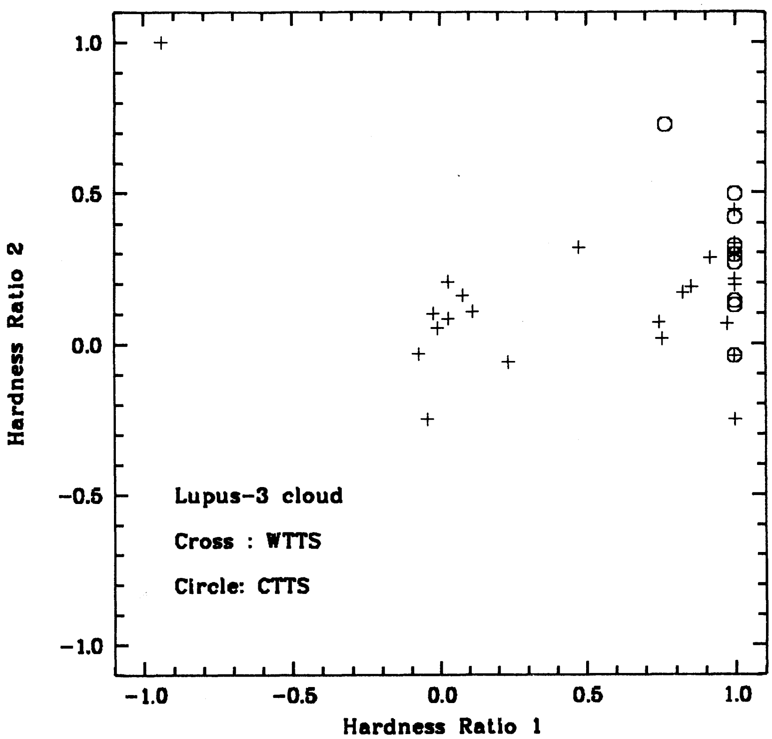

Fig. 6. Hardness ratios HR1 vs. HR2 for the WTTS (crosses) and CTTS (circles) in the Lupus-3 subcloud.

7.3. X-ray Luminosity Function

The X-ray luminosity function has been determined so far only for the central parts of the Chamaeleon SFR by Feigelson et al. (1993). The average X-ray luminosity $< log\, f_x >=$ 29.3 is significantly higher than the average X-ray luminosity in young clusters. However, since very faint sources could still be missing, this number is an upper limit of the X-ray luminosity only.

7.4. Temporal Variations

If one compares the two pointed exposures in the southern part of Chamaeleon (cf. Figure 2), one finds the same 'Christmas-tree' appearance as found by Montmerle et al.(1983), since several sources are detected in the 6 ksec exposure which do not show up in the 32.5 ksec exposure. However, no flare event could be found for the PMS stars in the 32.5 ksec exposure. A temporal analysis of the survey data is still under way, but obviously strong flare events are very rare.

7.5. Correlation of L_x with Stellar Parameters

Several correlations of the X-ray luminosity L_x with stellar parameters are well established, and others are still under discussion. Figure 7 shows a plot of log L_x vs. the mass for WTTS and CTTS in Orion and Chamaeleon and CTTS in Chamaeleon. A correlation between these two quantities is clearly visible. A similar result was found by Feigelson et al. (1993). This correlation is somewhat surprising, since it cannot be easily understood in terms of the dynamo model which is commonly accepted to explain the magnetic activity of the low-mass PMS stars. A similar dependence presented in Figure 8 for WTTS in Chamaeleon and Orion has been found for the bolometric luminosity L_{bol} vs. L_x. This is not surprising, since L_{bol} should in first approximation depend on the mass, and, hence, a correlation with L_x should exist, too. The same explanation holds for the correlation between L_x and T_{eff} found by Feigelson et al. (1993). Both our data as well as Feigelson et al.'s show that there is also a clear correlation between L_x and the radius R for the WTTS.

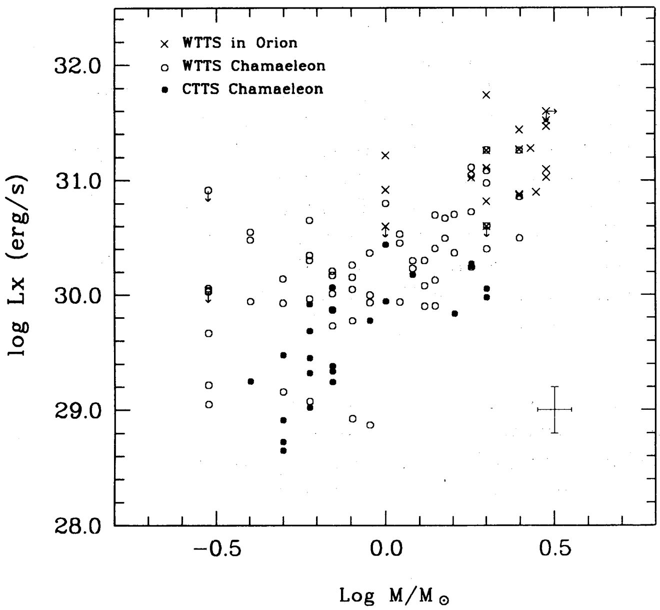

Fig. 7. L_x vs. mass for WTTS in Orion (crosses), and CTTS (dots) and WTTS (circles) in Chamaeleon.

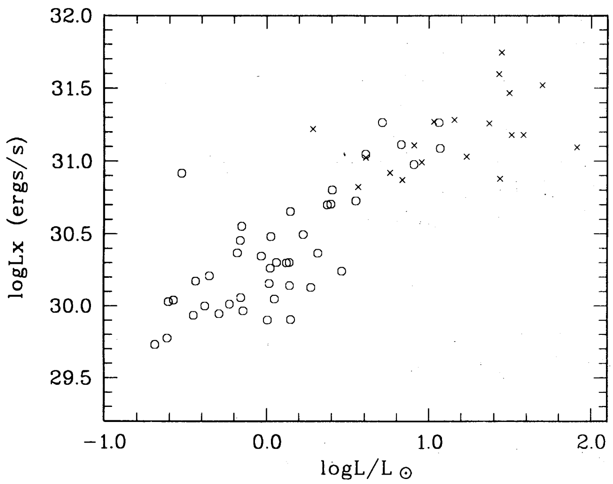

Fig. 8. L_{bol} vs. L_x for WTTS in Orion (crosses) and Chamaeleon (circles)

From our data no strict anti-correlation between L_x and the Hα equivalent width could be found. However, among the CTTS the stars with the highest equivalent widths of Hα tend to have the lowest L_x. No correlation between the X-ray surface flux and Hα equivalent width, as exists for magnetically active late-type stars, has been found either for CTTS or for WTTS.

A correlation between L_x and the rotational velocity vsin$i$ is neither obvious in our data nor in Neuhäuser et al.'s. However, since the determination of vsin$i$ requires high spectral resolution, only little observational material is available yet. It is, however, interesting to note, that Bouvier et al. (1993), who determined rotation periods from photometric observations, and Edwards (1994) found evidence that WTTS rotate on the average faster than CTTS. However, it cannot be excluded that this is due to a selection effect: both samples are rather small, and it could be, that stars with high masses and large rotation rates were preferentially observed.

8. CONCLUSIONS

ROSAT observations have turned out to be a very powerful tool of the study of the formation process of low-mass stars. For the first time, the *ROSAT* survey allows study of a spatially complete, flux limited sample of PMS stars. Here we have discussed the results we have obtained from several selected star forming regions. The *ROSAT* observations analyzed so far have demonstrated that WTTS are more numerous than CTTS by at least a factor of 1.5–2.5, but the real factor is even higher. WTTS have a much more extended spatial distribution than CTTS; they are tracers of the star formation history. The mean properties of WTTS differ in many respects from those of CTTS, e.g., they are older and more massive. The *ROSAT* data have only been partially analyzed and many surprising results are probably awaiting us in the future. However, one should always keep in mind that only in connection with follow-up observations in the optical and IR spectral range the X-ray data of star forming regions can be fully exploited.

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REFERENCES

Alcalá, J.M., Covino, E., Franchini, M., Krautter, J., Terranegra, L., & Wichmann, R. 1993, A&A, 272, 225
Ambartsumian, J.A. 1947, Stellar Evolution and Astrophysics (Erevan: Acad. Sci. Armenian)
Bisvonatyi-Kogan, G.S., & Lamzing, S.A. 1977, SvA, 21, 720
Bodenheimer, P. 1965, ApJ, 142, 451
Bouvier, J., Cabrit, S., Fernández, M., Martín, E.L., & Matthews, J.M. 1993, A&A, 272, 176
Braun, M. 1992, Diploma thesis, Universität Jena
D'Antona, F., & Mazitelli, I. 1994, ApJS, 90, 467
den Boggende, A.F., Mewe, R., Gronenschild, E.H.B.M., Heise, J., & Grindlay, E. 1978, A&A, 62, 1
Edwards, S. 1994, RevMexAA, 29, 35
Feigelson, E.D. 1987, in Protostars and Molecular Clouds, ed. T. Montmerle & C. Bertout, p. 123
Feigelson, E.D., Casanova, S., Montmerle, T., & Guibert, J. 1993, ApJ, 416, 623
Feigelson, E.D., & DeCampli, W.M. 1981, ApJ, 243, 289
Feigelson, E.D., & Kriss, G.A. 1981, ApJ, 248, L35
______. 1989, ApJ, 338, 262
Gahm, G.F., Fredga, K., Liseau, R., & Dravins, D. 1979, A&A, 73, L4
Herbig, G.H. 1962, Adv. A&A, 1, 47
______. 1978, in Problems of the Physics and Evolution of the Universe (Erevan: Acad. Sci. Armenian), p. 127
Herbig, G.H., & Bell, K.R. 1988, Lick Obs. Bull. No. 1111
Joy, A.H. 1942, PASP, 54, 15
Krautter, J., & Kelemen, J. 1987, Mitt. Astron. Ges., 70, 397
Krautter, J. 1991, in Low Mass Star Formation in Southern Molecular Clouds, ESO Report No. 11, ed. B. Reipurth, p. 127
Maddalena, R.J., Morris, M., Moscowitz, J., & Thaddeus, P. 1986, ApJ, 303, 375
Mendoza V., E.E. 1966, ApJ, 143, 1010
_____. 1968, ApJ, 151, 977
Montmerle, T., Koch-Miramond, L., Falgarone, E., & Grindlay, J. 1983, ApJ, 169, 182
Montmerle, T., & André, P. 1988, in Formation and Evolution of Low Mass Stars, ed. A.K. Dupree & M.T.V.T. Lago, p. 225
Mundt, R. 1981, A&A, 95, 234
Neuhäuser, R., Sterzik, M.F., & Schmitt, J.H.M.M. 1994, in Cool Stars, Stellar Systems and the Sun, Proc. of the 8^{th} Cambridge Workshop, ed. J.A. Caillault, in press
Pallavicini, G., Pasquini, L., & Randich, S. 1992, A&A, 261, 245
Pfeffermann, E., Briel, U.G., Hippmann, H., Kettenring, G., Metzner, G., Predehl, P., Reger, G., Stephan K.H., Zombeck, M.V., Chappell, J., & Murray, S.S., 1986, in Soft X-Ray Optics and Technology, Proc SPIE, 733, 519
Ruczinski, S.M., & Krautter, J. 1983, A&A, 121, 217

Schwarz, R.D. 1991, in Low Mass Star Formation in Southern Molecular Clouds, ESO Report No. 11, ed. B. Reipurth, p. 93
Trümper, J. 1983, Adv. Space Res., 2, 241
Walter, F.M., & Kuhi, L.V. 1981, ApJ, 250, 254
______. 1984, ApJ, 284, 194
Walter, F.M., Brown, A., Mathieu, R.D., Myers, P.C., & Vrba, F.J. 1988, AJ, 96, 297
Walter, F.M. 1990, in Imaging X-Ray Astronomy, ed. M. Elvis, p. 223

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