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X-RAYS AND LOW-MASS STAR FORMATION

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RESUMEN

Diez años después del lanzamiento del satélite *Einstein* de rayos X, la llegada de una nueva generación de satélites de rayos X (representada por *ROSAT* y *ASCA*) ha permitido un progreso espectacular en lo que respecta a la física de las estrellas, y en particular de las fases tempranas de la evolución estelar de estrellas de masa pequeña de la presecuencia principal. Además, datos más recientes están mostrando la importancia de las observaciones de rayos X en los estudios de la formación estelar. En este artículo discutimos dos problemas concretos: (*i*) Por medio de observaciones con *ROSAT* y *ASCA* se han detectado rayos X procedentes de objetos estelares jóvenes inmersos en la nube de ρ Oph con energías de hasta 10 keV. La irradiación del material interestelar denso por los rayos X tiene tres efectos principales: El nivel de ionización se incrementa en las proximidades de los objetos estelares jóvenes, lo que probablemente repercute negativamente en una formación estelar posterior; se modifica la química del gas molecular; y por último, se altera la composición de los granos de polvo más pequeños. Todos estos efectos no se conocen muy bien. (*ii*) El estudio del cielo con ROSAT ha permitido obtener evidencias sobre la existencia de ciertas estrellas T Tauri (algunas muy jóvenes) lejos de las regiones estándar de formación estelar. Esto plantea hoy por hoy un problema abierto de cómo y donde se han formado esas estrellas.

ABSTRACT

A decade after the launch of the *Einstein Observatory* X-ray satellite, the advent of a new generation of X-ray satellites (represented by *ROSAT* and *ASCA*) has allowed radically new progress as regards stellar physics, and in particular in the early pre-main-sequence phases of the evolution of low-mass stars. In addition, the most recent data bring new insights into the role of X-rays for star formation studies. We describe here two important challenges. (*i*) In long pointed observations, *ROSAT* and *ASCA* have allowed to discover X-rays of energy up to 10 keV from Young Stellar Objects deeply embedded in the ρ Oph core. X-ray irradiation of the dense cloud material has three major effects : ionization is increased in the vicinity of YSOs, likely having a negative feedback effect on further star formation; molecular gas chemistry is modified; the composition of the smallest dust grains is altered. All these effects are poorly known. (*ii*) The *ROSAT All Sky Survey* has yielded evidence for the existence of hundreds of T Tauri stars (some quite young) far from the "standard" star forming regions. The problem of how and where these stars formed is essentially open.

Key words: **ISM : DUST, EXTINCTION — STARS : FORMATION — STARS : PRE-MAIN-SEQUENCE — INFRARED : STARS — X-RAYS : STARS**

1. X-RAYS FROM T TAURI STARS

1.1. Early Results : The *Einstein* Era

With the first astronomical X-ray imaging satellite, the *Einstein Observatory* (1979-1982), decisive advances were made, in particular in stellar physics. An important contribution to stellar evolution was the discovery of young, low-mass stars, featuring strong X-ray emission but lacking the traditional signposts of youth such as emission lines (particularly Hα), UV and IR excesses, conspicuous in the T Tauri stars known at the time. Consequently, the new stellar population was dubbed the "weak" or "weak-line" T Tauri stars ("WTTS" for short; sometimes also called "naked" T Tauri stars), as opposed to the "classical" T Tauri stars ("CTTS" for short) known previously. The importance of this discovery stems mainly from the fact that the WTTS population outnumbers the CTTS population by factors $\sim$ 3 - 10 (according to different estimates, see § 3.1): the low-mass PMS stellar population is *de facto* largely dominated by the WTTS. It is now reasonably well established that CTTS are surrounded by dense circumstellar accretion disks, whereas, with a few exceptions, WTTS are not surrounded by optically thick circumstellar material (for reviews, see, e.g., Bertout 1989; Montmerle & André 1989; Feigelson, Giampapa, & Vrba 1991).

That WTTS were discovered via their X-ray emission is important, because this wavelength range stands out clearly against all the other stellar backgrounds. From the *Einstein* data, it could be concluded that there were no significant differences in X-ray properties between the two populations (see the absence of correlation with Hα emission equivalent width, for instance; e.g., Bouvier 1990), showing that the X-rays were purely stellar, and had little to do (if anything) with the presence of circumstellar material.

As seen by *Einstein*, the X-ray luminosities of both populations were high, in the range $L_x = 10^{30}$ to 10^{32} erg.s^{-1}, or 10^3 to 10^5 times the average solar luminosity $L_{x,\odot}$. The extinction of the detected stars was moderate, typically $A_V < 5$.

1.2. Mechanism for X-Ray Emission

All the available evidence (including the most recent results from *ROSAT* and *ASCA*, see § 1.3) suggests that the X-rays observed in TTS are thermal in nature (optically thin bremsstrahlung from a high-temperature plasma). What is not totally clear, however, is whether the plasma is at one temperature only, or whether there is a range in temperatures. In flares (see below), when the emission is strong and the X-ray counts are numerous, a one-temperature fit is found. An approximate average plasma temperature T_x of $\approx 10^7$ K (or an energy $kT_x \approx 1$ keV) is typical, with an electron density $n_e \approx 10^{10}$ to 10^{12} cm^{-3} (derived from the observed emission measures).

The X-ray emission is in general variable, often on time scales of hours. A number of events have been clearly identified as flares, with light curves showing on fortunate occasions both the rising and the declining phases. In general, the observed temperatures observed in flaring episodes are > 1 keV (e.g., Montmerle et al. 1984; Preibisch, Zinnecker, & Schmitt 1993), directly revealing the heating of the plasma. The values of the temperature and density, the variability timescales, the luminosity distribution, along with other characteristics of TTS seen in the optical like starspots, concur to indicate that the activity is fundamentally solar-like, and magnetic in nature. In turn, this suggests that the plasma is confined within magnetic loops. The derived values of the magnetic field are not extraordinary high ($B_\star \sim$ a few 100 G, rather typical of solar active regions), but the loop sizes may be very large : values derived from the X-rays may reach $\approx$ 2 - 3 stellar radii ($R_\star$) (see, e.g., the review by Montmerle et al. 1993).

This magnetic activity is thought to originate in the dynamo mechanism associated with convective motions in cool stars, but evidence for the dynamo interpretation of the activity at the TTS stage is not clear (see discussion in Feigelson et al. 1993, and Montmerle et al. 1994).

1.3. The *ROSAT/ASCA* Era

A new era in X-ray astronomy has begun in 1990, with the launch of *ROSAT*, followed by that of *ASCA* in 1993. Both satellites have the same kind of optics (nested annular grazing incidence mirrors) than *Einstein* (see Giacconi et al. 1981).

ROSAT is the product of a German-US-UK collaboration (Trümper 1990). It operates in the 0.1 - 2.4 keV energy range, and has two imaging detectors: the Position Sensitive Proportional Counter (PSPC), and the

High Resolution Imager (HRI). The PSPC has a much improved performance over that of the *Einstein* Imaging Proportional Counter (IPC): better sensitivity (by a factor ≈ 10 for long exposures) and angular resolution (error boxes less than 10″ along the axis), together with a larger field of view (2° in diameter), although the overall performance declines far off-axis. The energy resolution remains however modest ($E/\Delta E \approx 10$). The HRI is basically a copy of the one installed aboard *Einstein*, albeit more sensitive because of the larger mirror collecting area.

ASCA, a Japan-US collaborative effort, was designed as a high-throughput X-ray telescope (Tanaka, Inoue, & Holt 1994). It carries four grazing incidence mirrors, each equipped with an imaging spectrometer. It is the first image focusing satellite to reach hard X-ray energies, up to 10 keV. Also, the energy resolution is rather good, reaching $E/\Delta E \sim 50$ at 6 keV, and allows in particular to detect the Fe 6.7 keV line and important lines of other heavy nuclei. These lines constitute clear signatures of the thermal nature of the detected X-rays. The drawback is less sensitivity in the *ROSAT* energy range, and a modest angular resolution, $\approx$ 1' along the axis. One pair of telescopes has a square field of view (20' × 20'), the other has a circular field of view, 50' in diameter.

Also, it is useful for the present paper to recall that *ROSAT* has had successively two operating modes. The first six months were dedicated to scanning the sky with the PSPC, resulting in the "*ROSAT* All-Sky Survey" (RASS). The RASS sensitivity is comparable to that of *Einstein* pointed observations; so far, the X-ray data of 60,000 sources have been reduced (of which 40,000 are available on-line via the HEASARC database). Next, a pointed mode, both with the PSPC and the HRI, including guest observations, was implemented, which still works to this day (however, only the HRI is currently available). *ASCA* operates only in a pointed mode.

As the rest of the paper will show, *ROSAT* (and to a lesser extent *ASCA*) has an impact not only on PMS stellar physics, but also on the physics of the dense interstellar medium. Taking advantage of the large fields of view of the X-ray telescopes, our group has embarked on a program of a dozen *ROSAT* and *ASCA* pointed observations of the densest regions of several molecular clouds and neighboring areas (Chamaeleon, ρ Oph, and their vicinity; L1551, Mon R2, CMa R1, Rosette), with the aim of improving our knowledge of the evolution of young low-mass stars, from the earliest to late PMS stages, as well as of their possible interaction with dense interstellar material. Comparable studies have been undertaken by other groups, but such is the wealth of data that few have been published so far in refereed journals (see Caillault 1994 for a recent status).

2. X-RAYS AND LOW-MASS STAR FORMATION : "DEEP INSIDE"

2.1. *ROSAT* and *ASCA* Observations of the ρ Oph Core

Casanova et al. (1995) (hereafter CMFA) have obtained a deep exposure (33,000 sec.) of the central regions of the ρ Oph cloud with the *ROSAT* PSPC. This region is dominated by a dense $C^{18}O$ $(1 \rightarrow 0)$ core, itself divided into several DCO^+ sub-cores (see Loren, Wootten, & Wilking 1990). Low-mass star formation is known to be very active there, with more than 100 Young Stellar Objects (YSOs) known at many wavelengths, from *Einstein* X-rays to the millimeter range (see references in CMFA).

Fig. 1, which presents high-quality data obtained in the central 35′ × 35' of the PSPC field, summarizes some of the results, by highlighting three key ingredients (see CMFA for details). (*i*) The thin contours correspond to 1.0 - 2.4 keV X-ray counts smoothed with a 15″ FWHM gaussian. Fifty-five strong sources ($S/N > 3.25$) are clearly visible. In addition, about 50 weaker sources are significant at the $2 - 3.5\sigma$ level; not more than 10 may be attributed to statistical background fluctuations. Hence, altogether ≈ 100 X-ray sources are found with *ROSAT*. (*ii*) The crosses indicate 88 infrared sources which are *bona fide* cloud members. (*iii*) The thick dashed lines represent $C^{18}O$ $(1 \rightarrow 0)$ contours, with the associated visual extinction A_V contours indicated (from Wilking & Lada 1983). A clustering of both X-ray and IR sources is apparent near two of the sub-cores, with a large number of spatial coincidences (in general within a few arcsecs).

The same region has also been observed with *ASCA*, during a 38,000 sec. exposure (Koyama et al. 1994). Eleven sources are detected, all except two having IR counterparts identified with cloud members, showing that YSOs can emit hard X-ray photons up to ~ 10 keV. Almost all sources are time variable. Also, unresolved hard X-ray emission is detected from the central area, which is found consistent with the high-energy tail of the sources detected by *ROSAT*.

2.2. Nature of the X-Ray Sources

To understand the nature of the *ROSAT* sources found in the ρ Oph cloud, we use the standard YSO classification based on their spectral energy distribution in the IR and beyond, as originally defined by Lada

(1987), and recently revisited by André & Montmerle (1994) (see also the review by André 1994). The X-ray detection rate of the YSOs is high : overall, more than 70 % are detected. Using the X-ray/IR identifications, we find the following detection rates (ratio = percentage). Class III : 16/20 = 80 %; Class II : 31/43 = 72 %; Class I : (1-10)/15 = 7-67 % (see § 2.3); Class 0 : 0/1 = 0 %. The highest detection rates are thus found for Class III and Class II sources, consistent with their interpretation as embedded TTS undergoing magnetic activity.

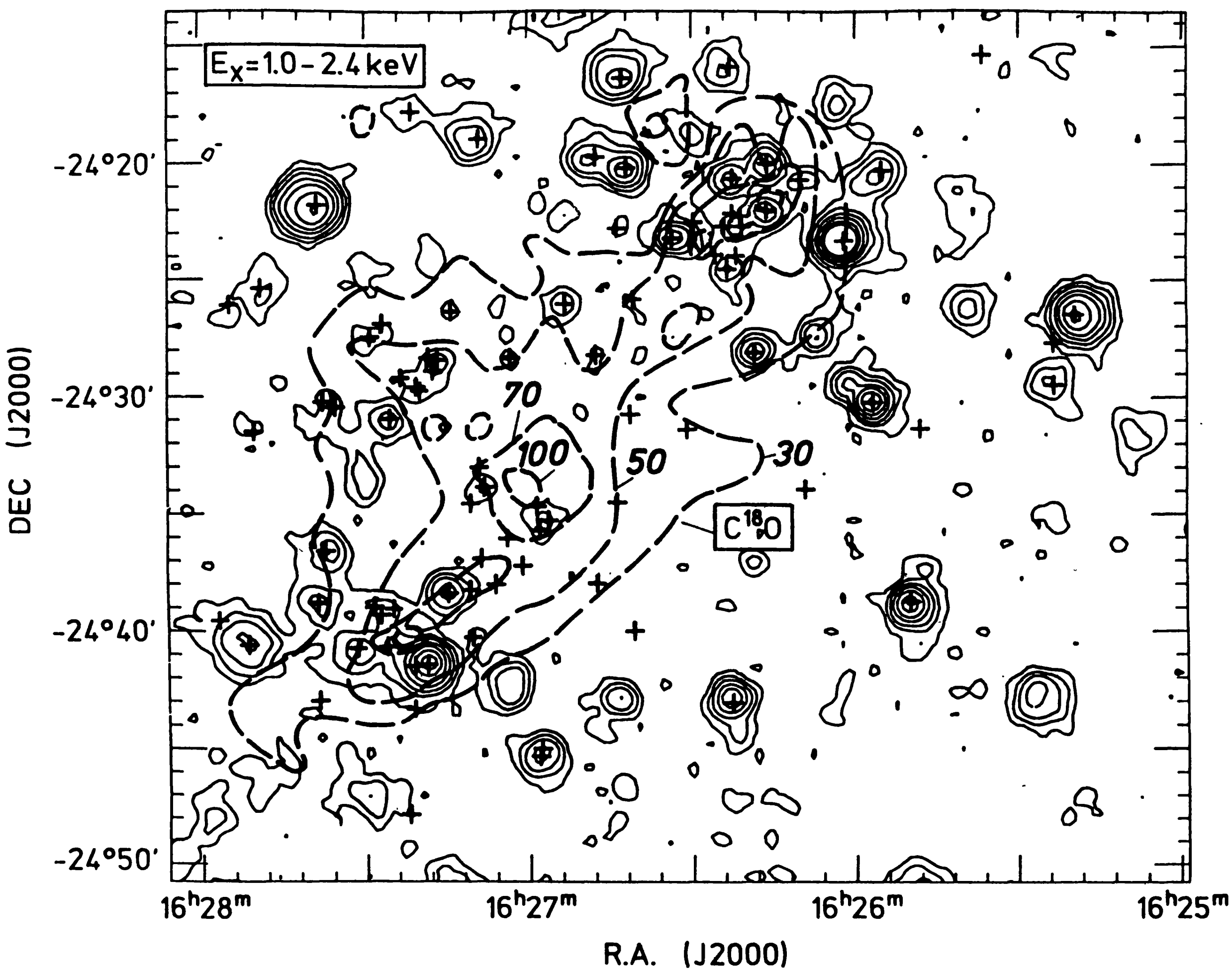

Fig. 1.— The ρ Oph core region at three wavelengths : *ROSAT* X-ray sources (thin contours), IR sources (plusses), and distribution of the molecular gas (traced by $C^{18}O$, dashed contours). (From Casanova et al. 1995).

To find the X-ray luminosities, we need to correct for extinction. We do this by using *JHK* photometry of the IR sources. Fig. 2 displays the number of *ROSAT* sources found with a given equivalent extinction in the visible $A_{V,IR}$. The fact that many X-ray sources have a high extinction (up to 40 or more) demonstrates that their clustering in the cores is not simply a projection effect, but that they are really deeply embedded in these cores. The resulting intrinsic *ROSAT* X-ray luminosities L_x range from $\sim 10^{28}$ to $\sim 3 \times 10^{31}$ erg.s^{-1} : the faintest L_x are $\sim$ 100 times lower than were accessible with *Einstein*. A plasma temperature can be derived from the X-ray spectrum only for the strongest sources : it is consistent with $kT_x \approx 1$ keV. The corresponding total X-ray luminosity is $L_{x,Oph} \approx 6 \times 10^{32}$ erg.s^{-1}. In the *ASCA* band, where essentially no extinction correction is required (see below), the total X-ray luminosity (including the unresolved sources) is of the same order as in the *ROSAT* band.

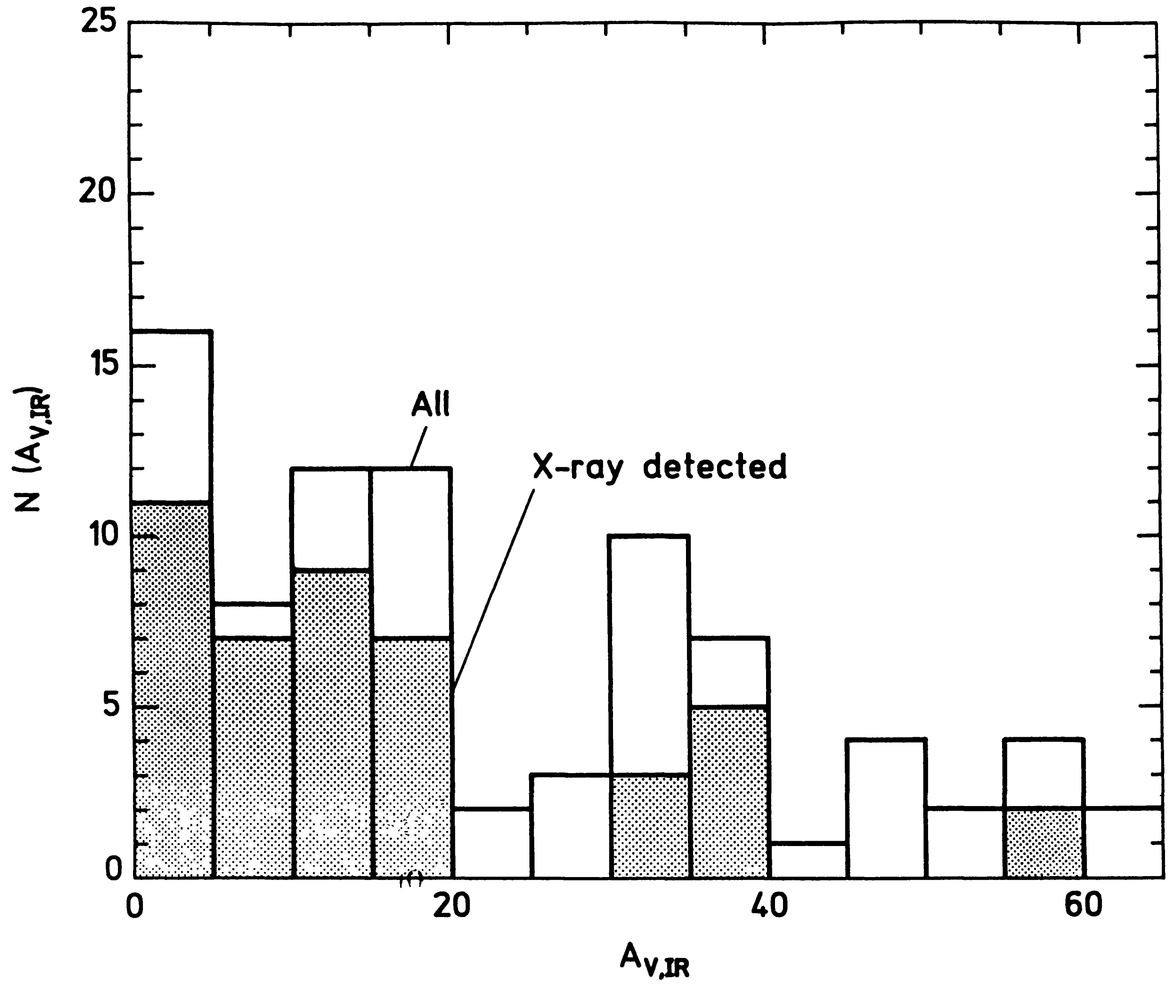

Fig. 2.— Number of X-ray and IR sources in the ρ Oph core, as a function of $A_{V,IR}$, the equivalent visual extinction derived from near-IR photometry (Casanova et al. 1995).

It is important to note that the ability to detect X-rays from such deeply embedded sources stems from the fact that CMFA have selected X-rays above 1 keV. Roughly speaking, the X-ray absorption varies as $E^{-2.5}$, and lower energy X-rays are indeed efficiently absorbed. But by a remarkable "cosmic conspiracy", the extinction cross-section for X-rays of energy $\simeq$ 1 keV turns out be *identical* to that in the near-IR range, within a factor of 2 (for details, see CMFA, Appendix A2, and Casanova 1994).

The near-IR data can also be used to derive the bolometric luminosity L_{bol} of the X-ray sources. Indeed, based on a recent sensitive near-IR survey of the ρ Oph core, Greene et al. (1994) have used dereddened J magnitudes (essentially insensitive to circumstellar material) to show that $L_{bol} \propto L_J$ in the case of Class II and Class III sources. (This result can be understood on theoretical grounds, see Greene et al. for details.) Plotting the resulting L_x vs. L_{bol} diagram, CMFA find a tight correlation between the X-ray and bolometric luminosities: $L_x = 10^{-4} \times L_{bol}$. (For comparison, $L_{x,\odot} \sim 10^{-6} \times L_{bol,\odot}$.) An interesting consequence is that a deep *ROSAT* exposure like that obtained on ρ Oph turns out to be as sensitive to YSOs as near-IR arrays of the NICMOS type (limits : PSPC count rate $\sim$ 0.1 ksec^{-1}, $J \sim 16$) !

The L_x vs. L_{bol} correlation is almost identical to that found for TTS stars (CTTS and WTTS alike) by Feigelson et al. (1993) in the Chamaeleon I cloud, and confirmed by Neuhaüser et al. (1995) on the Taurus clouds. Although such a correlation is not understood theoretically, it is a further proof that Class II and Class III sources are indeed obscured TTS. A comparison between the X-ray luminosity functions for deeply embedded sources (dominated by Class II) and less embedded sources (dominated by Class III) shows that they are statistically indistinguishable, reinforcing the *Einstein* results that X-ray properties of CTTS and WTTS are basically identical, whether they are embedded or not (see also the discussion in Feigelson et al. 1993).

2.3. Are Protostars X-Ray Emitters?

It is important to establish whether protostars are X-ray emitters, if only to "date" the appearance in their center of a real stellar object with magnetic activity. As mentioned above, the youngest object in the studied area, the Class 0 source VLA1623 (André, Ward-Thompson, & Barsony 1993), is not detected. But its huge internal extinction ($A_V \approx 1000$) can easily explain this non-detection. For Class I sources, the present situation is unclear, because of confusion : 7 *ROSAT* sources include Class I sources in their error box, but (with one exception) they also include other IR sources of a different class or unclassified (see Table 1).

Table 1. X-ray sources coincident with Class I YSOs in the ρ Oph core region

ROXR1	Class I source	Other IR source in the *ROSAT* error circle
22	GSS30-IRS 1 LFAM 1	GSS30-IRS 2 (Class III)
C5	GY 224	...
C7	WL 6 GY 256	GY 257 (flat spectrum)
43	IRS 43	GY 263 (unconfirmed member)
45	IRS 44 IRS 46	GY 262 (Class II)
C10	IRS 54	GY 388 (unconfirmed member)
C11	IRS 48	IRS 50 (unclassified confirmed member)

The situation should be settled soon, with the availability of *ROSAT* HRI data, which are obtained with enough angular resolution to solve the pending identification problems. Finally, it is interesting to note that two Class I sources (GY 256 and WL 6) lie in the error box of one of the *ASCA* sources.

2.4. Ionization Effects and Feedback on Star Formation

The high concentration of X-ray sources in dense cores provides a source of ionization for the molecular gas. In turn, this ionization is important for star formation because it couples the essentially neutral gas ($n_e/n_H \sim 10^{-7}$) to magnetic field lines, and controls gravitational collapse through ambipolar diffusion, i.e., ion-neutral collisions (e.g., Shu, Adams, & Lizano 1987).

As shown by Krolik & Kallman (1983 (heareafter KK; see also Silk & Norman 1983) after early *Einstein* results, X-ray ionization in molecular clouds proceeds in two steps: (*i*) photoionization of the molecules (ejection of one Auger electron from an inner shell), and (*ii*) cascading subsequent ionizations of other molecules by the Auger electrons. KK show that collisional ionization by these electrons is ~ 10 times more efficient than direct photoionization. From their work, CMFA derive the ionization rate in the ρ Oph core by ~ keV X-rays $\zeta_{x,Oph}$, as a function of the optical depth to these photons τ_x as:

$$\zeta_{x,Oph}(1 \text{ keV}) \sim 1.3 \times 10^{-14}\, \tau_x^{-1.6} \ \text{s}^{-1}.$$

In the ρ Oph core, the total extinction is $A_V \approx 100$, which corresponds to $\tau_x \sim 40$ at 1 keV. Thus, the minimum ionization rate in this region is $\sim 3.5 \times 10^{-17}$ s^{-1}. This is higher than the average ionization rate deduced from molecular cloud chemistry and generally attributed to low-energy cosmic rays, indicating that X-ray ionization must indeed be considered when discussing star formation. In addition, and contrary to cosmic rays, which more or less pervade molecular clouds uniformly and independently of their stellar content, the fact that the ionizing source has its origin in the YSOs themselves suggests a *feedback mechanism* on further star formation in their vicinity. According to early calculations by Silk & Norman (1983), the net effect of X-ray ionization by embedded objects should be a decrease in the overall star formation efficiency (i.e., a negative feedback).

Incidentally, other important effects can be expected from X-ray irradiation of molecular gas and dust : modification of chemical reactions (mostly those involving radicals, see KK for an early work), of dust grain composition (for instance, vaporization of the smaller grains, see Voit 1991), etc. But altogether very little is known to date on these effects, and it is hoped that the above results will stimulate further work.

3. X-RAYS AND LOW-MASS STAR FORMATION: "FAR OUTSIDE"?

3.1. T Tauri Stars far from Molecular Clouds

It is already known that some TTS may be found far from molecular clouds, or, more generally, at high galactic latitudes. Current studies, however, rely mostly on searches for IR-excess objects in the *IRAS* Point Source Catalog (Gregorio-Hetem et al. 1992, Magnani et al. 1995), so they *a priori* select the CTTS type. Only a dozen confirmed cases have been found so far, although $\sim$ 200 candidates have been identified at $| b | \geq 30°$. By contrast, X-rays, which we have seen are very efficient to detect young stars in general (for instance using their high L_x/L_{bol} ratio), may be used to efficiently detect WTTS (in addition to CTTS), particularly in the case of the RASS, which is moderately sensitive but allows to study vast areas of the sky.

To illustrate this point and its consequences, we now briefly report on the recent results of three large-area surveys (Alcalá 1994; Neuhäuser et al. 1994, 1995; Sterznik et al. 1995), in the Taurus-Auriga, Chamaeleon, and Orion regions.

(*i*) *Taurus-Auriga.* In a first work, Neuhaüser et al. (1995a) have studied the "normal" star-forming region Taurus-Auriga, looking for the X-ray emission of 153 already known TTS (from the Herbig & Bell catalog) over $\sim$ 1000 sq. degrees. The RASS shows in this area about 1900 other sources which cannot be identified with cataloged stars or extragalactic objects. The high detection rate of WTTS (66 %) among the known TTS suggests that many could exist among the unidentified RASS sources. Indeed, by applying a selection criterion based on the X-ray hardness ratio of the identified WTTS, Neuhäuser et al. (1995b) estimate that about 1,000 new ones should be present in the area, thereby confirming the high WTTS/CTTS ratio ($\sim$ 10) found by Walter et al. (1988) using *Einstein* IPC data. These WTTS candidates are spread over all the large area studied, indicating that many must lie far from dense cores or filaments (where most of the known CTTS are located).

(*ii*) *Chamaeleon.* Over an area of $\sim$ 200 sq. degrees including the Cha clouds, the RASS contains 181 sources. (By contrast, over $\sim$ 50 were found in the Cha I cloud alone with pointed observations, see Feigelson et al. 1993.) The cross-correlation of their positions with Simbad objects leaves 85 new TTS candidates, all of the WTTS type. Ground-based spectroscopy confirms the youth of these stars, with the detection of the λ6707 absorption line of lithium, and allows to put them on an HR diagram, assuming that they are all at the same distance as the Cha clouds themselves ($\sim$ 140 pc). As illustrated in Fig. 3, the spatial location of these WTTS is remarkable : most lie far (several degrees, i.e., several times 2.4 pc) from the Cha clouds, while, using e.g., the D'Antona-Mazitelli (1994) PMS evolutionary tracks, many appear very young ($\simeq 10^5$ yrs).

(*iii*) *Orion.* The case of the Orion region is significantly more complicated, because of the large number of stars involved. Over an area of $\sim$ 450 sq. degrees encompassing the giant molecular clouds, 820 RASS sources are found (Alcalá 1994). Identifications within the Simbad database leave no less than 470 TTS candidates : 98 new WTTS have been discovered so far by the same spectroscopic method as above. Sterznik et al. (1995) have reexamined the problem, over an even larger area of $\sim$ 710 sq. degrees, but using a statistical approach. Based on a number of identification criteria (spatial coincidences with stars in the Guide Star Catalog, X-ray hardness ratios and X-ray/optical flux ratios), these authors define a probability for a RASS source coinciding with a star to be a WTTS (see Sterznik et al. for details). After testing successfully their method against the spectroscopically identified WTTS in the region, they find 1081 *ROSAT* sources with a high WTTS probability, and reject the 1176 others. They identify spatial concentrations of WTTS candidates near the Orion OB 1a,

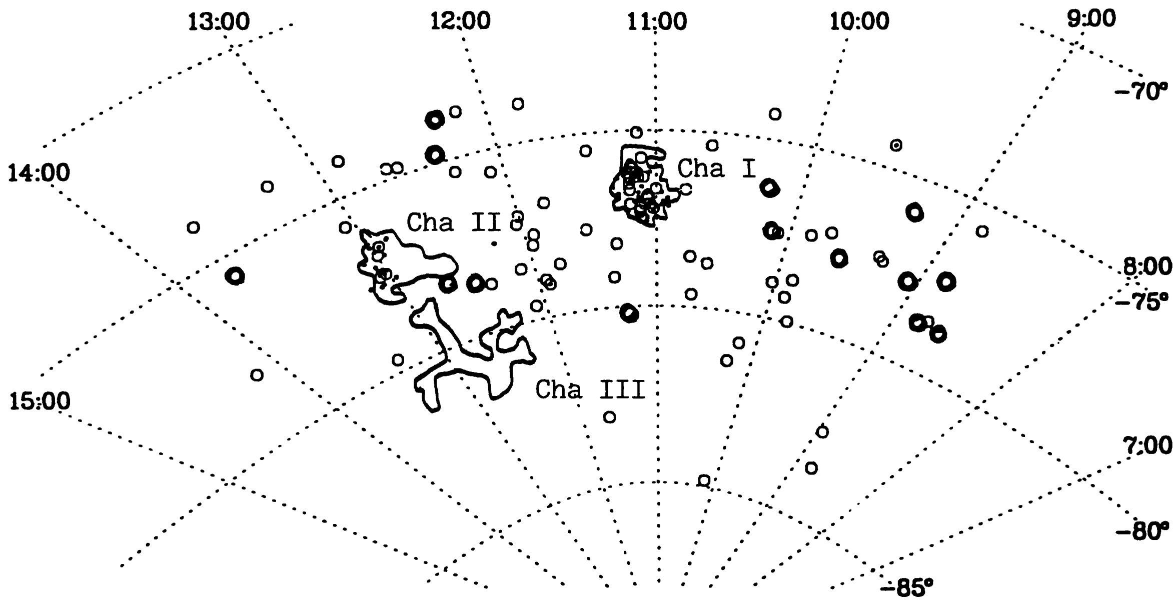

Fig. 3.— Spatial distribution of X-ray discovered and spectroscopically identified TTS in the Chamaeleon region. The well-known Cha I and Cha II star forming regions are indicated (contours). Dots : CTTS. Open circles : WTTS. The thick open circles indicate the youngest WTTS (ages $\sim$ a few times 10^5 yrs. (After Alcalá 1994.)

1b, 1c, and λ Ori associations, but find other previously unknown concentrations as well. The total population of WTTS candidates is spread over a very large area, again suggesting the presence of young stars far from molecular clouds.

3.2. Where were they Born?

The presence of TTS far from molecular clouds is a problem, since, at least for the youngest ones ($\simeq 10^5$ yrs), they are at distances larger than (age $\times$ drift velocity), taking a typical drift velocity of a few km.s^{-1}. While there are assumptions and uncertainties (like their exact distance, for example), the relevant TTS population is so large that the result must be, at least in part, real.

There are essentially two possibilities for their birthplaces. (*i*) In reality, the TTS were born elsewhere, for instance in the nearest molecular cloud, and have very large drift velocities. This is conceivable if they were initially in a binary or multiple system and were dynamically ejected, since it now appears that the percentage of binary systems is generally higher among YSOs ($\sim$ 70%) than for main sequence stars ($\sim$ 50%). It remains to be seen, however, whether such events may have occurred frequently enough in a star forming region like Orion. (*ii*) They were born at (or very close to) the location in which they are now found. A possibility is that they were born in "translucent" clouds (i.e., low-density molecular clouds; see Magnani, Blitz, & Mundy 1985) : a few CTTS are indeed known there, although a recent search in X-rays using the *Einstein* database (Caillault, Magnani, & Fryer 1995) has yielded no new TTS candidate (WTTS or CTTS). Star formation in these clouds thus seems feeble at best. In some places, it may have been triggered by the impact of high-velocity clouds (see Lépine & Duvert 1994), or by supernova explosions (see Barnard's Loop in Orion).

To answer the question of the origin of these TTS away from molecular clouds, systematic studies of the distribution and nature of the interstellar matter along the lines of sight to the newly identified RASS sources, using such databases as the *IRAS* 100 μm maps or the new Leiden/Dwingeloo HI survey (Hartmann & Burton 1995), are now needed.

4. CONCLUSION

In this paper, we have attempted to show that results on YSOs obtained in the X-ray domain may have a significant impact on star formation studies. The reason fundamentally lies in the high contrast of the (hot) X-rays as compared to other (mostly cold) tracers of YSO formation and evolution, as well as, probably, the ubiquity of the magnetic activity giving rise to these X-rays, of course combined with the increased sensitivity of the currently available detectors. We note that the strong links described in this paper between X-rays and the near-IR for YSOs in molecular clouds could also be efficiently used in large areas of the sky by combining *ROSAT* data (pointed or RASS) with IR surveys near 2 μm like DENIS (I, J, K bands, southern hemisphere, early phases in progress) or 2MASS (J, H, K bands, both hemispheres, just funded).

Two areas are particularly challenging for star formation theories. (*i*) "Hot in cold": X-rays are detected from very early PMS stages, perhaps as early as Class I (age $\sim 10^5$ yrs). X-ray irradiation within the dense molecular cores by YSOs directly provides a significant ionization in addition to that caused by low-energy cosmic rays, and probably results in a negative feedback mechanism on further star formation in their vicinity. Other X-ray irradiation effects, on molecular chemistry and dust grain composition, may be important but are poorly understood so far. (*ii*) "Hot in what ?": X-rays, this time used as a tracer of the existence of hundreds of TTS far from molecular clouds, may have revealed that star formation takes place on large spatial scales even at high galactic latitudes, albeit at a very low rate, in quite poorly known conditions.

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