Chandra Studies of Star Forming Regions

Eric D. Feigelson

Dept. of Astronomy & Astrophysics, Pennsylvania State University,
University Park PA 16802 USA

Abstract. When observed with sufficiently high spatial resolution and sensitivity, star formation regions are unusually complex X-ray sources. Low-mass protostars and T Tauri stars, Herbig Ae/Be stars, O B and Wolf-Rayet stars are seen at levels $28 \leq \log L_x \leq 34$ erg/s. High-amplitude variability from magnetic reconnection flares are often present. From past star formation episodes, supernova remnants and X-ray binary systems may dominate the emission on large scales. Astrophysically, ionization of molecular material from young stellar X-rays which may have important consequences for circumstellar disk evolution, bipolar flow ejection and star formation.

We report here early results from Chandra X-ray Observatory studies of a wide range of star forming regions using the ACIS camera. They include portions of the nearby Ophiuchus and Perseus clouds, the Orion Nebula Cluster (ONC) and elsewhere in the Orion giant molecular clouds, molecular clouds and star clusters around the Galactic Center, the 30 Doradus region of the LMC, and the prototype starburst galaxy M 82.

1. Introduction

The astrophysics of star formation and the early phases of stellar evolution have proved to be very complex phenomena that are currently under intense study. The traditional model of collapse of a uniform molecular cloud core when the gravitational force exceeds the thermal gas pressure (the Jeans criterion) is far too simple. Turbulent and magnetic pressures are comparable to thermal pressures in cloud cores, and the cores themselves race around supersonically within the giant molecular clouds (GMCs).

Even after loss of angular momentum via fragmentation, a significant fraction of the collapsing material enters a circumstellar disk rather than the protostar. The star-disk system drives powerful outflows, both highly collimated high-velocity Herbig-Haro objects and broader slower molecular bipolar flows. At the same time, material accretes onto the star, most likely funneled along magnetic field lines and the star contracts along the pre-main sequence convective Hayashi tracks towards the Zero-Age Main Sequence. The formation of high mass OB stars is enigmatic, as the Eddington limit should inhibit their formation from direct gravitational collapse. The recent reviews in Protostars and Planets IV (Mannings et al. 2000) and the monograph by Hartmann (1998) describe our current understanding of these issues.
Initially, there seems to be little role in the star formation story for high energy processes: the molecular clouds have temperatures $T \sim 10$ K, the young stellar surfaces have bolometric $T \sim 2000 - 3000$ K with disk temperatures roughly in the range $T \sim 100 - 1000$ K. Galactic cosmic rays are thought to provide a low uniform level of ionization through molecular clouds, but it has not been clearly established that most can penetrate the magnetic fields of the cloud and outflows.

It was thus a surprise in the early 1980s when the *Einstein* imaging X-ray telescope first pointed towards nearby star forming regions and found many hard, variable X-ray sources associated with young stars. Studies with *ROSAT* and *ASCA* in the 1990s found hundreds of young stars within star forming regions, and thousands of somewhat older pre-main sequence stars across the sky. It was established that T Tauri stars (ages $t \sim 1 - 20$ Myr) all emitted X-rays at levels $10^{1} - 10^{4}$ times those seen in normal old main sequence stars like the Sun, and that at least a few protostars ($t \sim 0.1 - 1$ Myr) also emit at very high levels. X-ray flares, typically lasting hours, similar but more powerful than those seen in the Sun and dMe flare stars, are often present. These X-ray findings and related astrophysical issues are reviewed by Feigelson & Montmerle (1999, henceforth FM99).

Most of the past X-ray studies (and closely related multiwavelength observations of magnetic activity and flares in PMS stars) have been made in the nearest, rather small star forming molecular clouds at distances $d \sim 150 - 450$ pc. Only small glimpses of star formation regions were possible in the truly giant cloud complexes at distances $d \sim 2$ kpc, across the Galaxy and in nearby galaxies like the LMC. Demographics of star forming regions indicates that most stars form in such rich stellar clusters from GMCs.

The *Chandra X-ray Observatory*’s high spatial resolution and sensitivity to hard photons, which penetrate both the local molecular cloud and intervening spiral arms, provide an enormous increase in capability for detailed study of star forming regions, particularly those beyond the solar neighborhood.

### 2. Expected X-ray emission from star forming regions

Figure 1 is a cartoon of a typical GMC from the X-ray point of view. Three typical situations are shown: an optically visible OB association at the edge of the GMC producing a blister H II region; an embedded OB association seen in K-band or mid-infrared observations producing (ultra-)compact H II regions; and distributed star formation. The diagram is not to scale: the GMC is an inhomogeneous and probably turbulent structure $\sim 100$ pc in size, while the young star clusters are typically $1 - 2$ pc in size. The X-ray components of a star forming region can be categorized as follows:

**T Tauri stars** The most numerous X-ray source type found in star formation regions are low-mass PMS stars ($M \leq 2$ M$_{\odot}$) with a broad X-ray luminosity function ranging from $< 10^{28}$ erg/s for the least massive brown dwarfs to $10^{31}$ erg/s for the most luminous massive members of the class. The X-ray are produced both from classical T Tauri stars with star-disk accretion and ejection and from weak-lined T Tauri stars where the disk is largely dissipated. Flares with timescales of hours are often seen in these X-ray sources. The astrophysical
Figure 1. Diagram of the expected X-ray components from a giant molecular cloud with a blister HII region, embedded young star cluster and distributed star formation. Symbols: ⋆ = OB stars; × = Herbig Ae/Be stars; ⋄ = T Tauri stars; + = protostars; □ = X-ray binary system. Hatched region outside of the cloud represents a supernova remnant, and shaded regions within the cloud represent partially ionized X-ray dissociation regions.

origin is readily attributable to solar-type magnetic activity: plasma heated to $10^7$ K temperatures in multipolar magnetic field loops rooted onto the stellar surface (FM99).

**Protostars** Prior to Chandra, only a small fraction of protostars were detected in X-rays, but these often exhibited unusual properties: X-ray temperatures approaching $10^8$ K, some very powerful flares, and in one case, an iron emission line possibly indicating fluorescence off of a cold disk. Here it is possible that the magnetic reconnection involves long field lines connecting the protostars to the disk (FM99).

**Herbig Ae/Be stars** These intermediate mass pre-main sequence stars with star-disk interactions show X-ray emission ranging in the range $10^{29} - 10^{31}$ erg/s. Recent ASCA observations have detected flares supporting a magnetic reconnection origin as in lower mass stars (Hamaguchi et al. 1999).

**OB and Wolf-Rayet stars** These massive stars typically emit X-rays in the $10^{32} - 10^{34}$ erg/s range, and the emission is attributable to shocks in the line-driven wind, as an approximate relationship $L_x \propto L_{bol} \propto L_{wind}$. Extremely massive stars ($M > 50 \, M_\odot$) evolve so quickly that post-main sequence supergiants, including Wolf-Rayet stars, can coexist with pre-main sequence stars in a
single rich young stellar cluster. X-ray spectra are generally soft, except in close binaries of very massive stars where the colliding winds shocks attain $10^8$ K.

**Supernova remnants** Massive supergiants quickly undergo supernova explosions and the resulting ejected remnants which are strong X-ray emitters for $\sim 10^9$ yr. This coexistence of stellar birth and death generally occurs only in the most massive star forming regions; for example, in the discussion below it is seen in 30 Doradus but not in Orion. Supernova remnant X-ray luminosities usually lie in the range $L_x \approx 10^{35} - 10^{37}$ erg/s with spatial scales around $10^{-1} - 10^1$ pc.

**X-ray binary systems** X-ray binaries are close binary systems where one member is a compact stellar remnant accreting from its companion via Roche lobe overflow or a stellar wind. While the spatial association between star forming regions and X-ray binaries may be tenuous due to the delay in forming accreting systems, X-ray binaries can outshine all other X-ray components with $L_x \approx 10^{36} - 10^{40}$ erg/s. Helfand and Moran (2001) have estimated that 2–5% of OB stars eventually produce a high-mass X-ray binary, 0.1–0.2% are currently in that phase, and the X-ray binary luminosity is $2 - 20 \times 10^{34}$ erg/s per O star.

3. Early Chandra observations

I outline briefly some of the studies underway during the first year of Chandra operations, starting with nearby molecular clouds producing small clusters of lower mass stars and ending with galactic scale starbursts dominated by massive star formation. As this review is being written in November 2000, many results are still in a preliminary stage of analysis and interpretation.

3.1. $\rho$ Ophiuchus cloud

The $\rho$ Ophiuchi cloud is one of several molecular cloud complexes lying $\approx 150$ pc from the Sun on the periphery of the Local Hot Bubble. It consists of several dense cloud cores about 0.2 pc in size now actively forming stars lying at the head of a cometary cloud complex about 10 pc in extent. The star formation may have been triggered by the O-star winds of the nearby Sco-Cen OB association.

In the first year, Chandra is obtaining two deep $\sim 100$ ks ACIS exposures of the Core A and Cores E/F regions, and a mosaic of seven shallow $\sim 5$ ks exposures of outer cloud. In the mosaic, about 100 sources, mainly from classical and weak-lines T Tauri stars (Grosso et al., in preparation).

In the deep image of Cores E/F, 87 sources are detected; for comparison, the ROSAT HRI detected only 8 sources in the same region (Iminishi et al. 2001). In addition to T Tauri stars, a remarkably high fraction of Class I protostars are detected: 15 out of 21 in the field. Thus in a single image, Chandra provides more X-ray detections than obtained from the entire ROSAT and ASCA missions combined! This also demonstrates that elevated X-ray emission is a generic property of low mass stars in their Class I phase, and is not restricted to a few unusual systems. Ten Class I sources exhibited X-ray flares during the observation, clearly demonstrating that violent magnetic reconnection events produce protostellar X-ray emission. Finally, the X-ray spectrum of Class I protostar YLW 16A shows a strong fluorescent Fe 6.4 keV line, directly demonstrating that X-rays will shine upon and ionize the circumstellar disk (see §5).
3.2. Perseus molecular cloud

Chandra has scheduled observations of the two rich star clusters in the Perseus molecular cloud ($d \approx 350$ pc): IC 348 with stars several Myr old, and NGC 1333 with stars $\leq 1$ Myr old. The protostars of NGC 1333 produce over a dozen powerful bipolar flows which are violently stirring up the cloud. Preliminary examination of the 50 ks ACIS exposure of NGC 1333 shows over 80 X-ray sources, most associated with embedded members of the star cluster known from K-band studies (Feigelson et al., in preparation). Spectral types of X-ray detected sources range from mid-M to mid-O. The pattern of X-ray emission is not always straightforward: for example, the M4 star ASR 7 with $A_V \approx 20$ shows more X-ray counts than the nearby O6 star ASF 8 with $A_V \approx 7$. In contrast with the $\rho$ Ophiuchi cloud, most of the Class 0 and I protostars in the NGC 1333 field are not detected,
3.3. Orion molecular cloud complex

The early Chandra program includes intense study of the nearest giant molecular clouds at $d \approx 450 - 500$ pc, including several deep observations of the Orion Nebula region and several exposures elsewhere in the Orion A and B clouds.

The Chandra images of the ONC are spectacular with over a thousand sources detected in a single field – a record for X-ray astronomy. The technical achievements of these observations are truly impressive: sources are detected as faint as $\approx 6$ photons (limiting $L_x \approx 1 \times 10^{28}$ erg/s, better than the most sensitive ROSAT study of even the nearest star forming regions), stars detected embedded up to $A_V \approx 60$ magnitudes ($N_H \approx 1 \times 10^{23}$ cm$^{-2}$), binaries resolved on-axis as close as $2''$ (1000 AU), and absolute astrometry achieved to $\pm 0.1''$ on the Hipparcos reference frame (Garmire et al. 2000). About half of the ONC cluster members are detected with a strong mass dependence: virtually all of members above 1 M$_\odot$, stars between 0.2 – 1 M$_\odot$ if the absorption is not too high, and very few of the very low mass stars and brown dwarfs.

A few of many specific results expected from these observations have been described (Garmire et al. 2000, Schulz et al. 2001a). A wide range of variability behavior is seen. A few sources are invisible except during flares lasting several hours, and there may be a trend towards high variability for stars with higher absorption. X-rays are seen from young stars both with and without circumstellar disks, including those embedded in ionized globules seen in HST images. A considerable fraction of the known radio-emitting young stars in the ONC are detected; in most cases, the radio continuum is non-thermal gyrosynchrotron emission associated with powerful magnetic flares. Examination of the evolution of X-ray luminosity among a subsample of solar-mass stars suggests a previously unreported effect: emission appears uniformly high ($L_x \approx 2 \times 10^{30}$ erg/s) during the first 1 – 2 Myr, but diverges between high and low emitters at ages around 2 – 10 Myr. This may be explained by theories of the regulation of stellar angular momentum by magnetic coupling with circumstellar disks.

Observations of the ONC Trapezium stars provide a new detailed view of OB X-ray emission (Schulz et al. 2001a and 2001b). The most massive members, $\theta^1$ Ori A, C and E with spectral types O7–B0.5 have $L_x \approx 2 - 20 \times 10^{31}$ erg/s, while the less massive $\theta^1$ Ori B and D with spectral type B1 emit only $L_x \approx 5 - 10 \times 10^{30}$ erg/s, comparable to typical lower-mass T Taur stars. Chandra grating observations of the most luminous $\theta^1$ Ori C component reveals 30 lines from six elements (O, Ne, Mg, Si, S and Fe) with line ratios indicating a wide range of temperatures ($0.5 - 60$ MK) and densities ($0.3 - 9 \times 10^{13}$ cm$^{-3}$). Many lines are resolved with Doppler widths ranging from $\sim 400$ to 2000 km/s with a trend of higher velocities for the higher energy lines. The temperatures are considerably higher than predicted from the long-standing model of instabilities in a line-driven wind – emission from thin dense shells far out into the wind is a more promising approach.

In addition to the astrophysical insights likely to emerge from the new spectroscopy of young OB stars, the astronomical implications are clear: if OB stars typically have significant fractions of their hot plasma at energies in excess of 2 – 3 keV, then these stars will be detectable even through the densest molecular cloud interiors and intervening Galactic obscuration. The 2 – 6 keV bandpass is comparable to the mid- to far- infrared bands in its ability to penetrate high
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column densities. Chandra and XMM can thus study massive star formation throughout much of the Galactic disk. Early indications of this can be seen in the Orion Nebula field: mid-infrared Source n, one of the BN/KL cluster members, is faintly detected in the ACIS image, and a deeply embedded source $1.1''$ from the BN object itself are weakly detected in the $2 - 8$ keV band. It is not clear whether the latter is produced somehow by the massive BN object (shocks in its outflow?) or is due to an unusual previously unknown lower mass star. The hard X-ray emission of OB stars may also have important implications for the ionization of molecular cloud cores (§5 below).

Several Chandra observations are being made in the Orion giant molecular clouds away from the Orion Nebula itself. A short 2 ks observation of a field $1^\circ$ to the south in the Orion A cloud reveals 18 T Tauri stars with spectral types from A0 to M5 (Pravdo et al. 2001). Comparison with Einstein and ROSAT observations of the same field gives a 20-year baseline for variability studies. This and similar studies may also help define the ratio of stars formed inside and outside of rich clusters: X-ray surveys exclusively isolate pre-main sequence stars, while K-band observations of unconcentrated regions of star formation are frequently overwhelmed by background sources.

A remarkable field has been studied $0.2^\circ$ north of the Orion Nebula, pointed at the filament-shaped OMC 2/3 dense molecular cloud cores. Millimeter studies have shown this is a site of intense current star formation with up to 30 likely protostars of Class 0 and I. In a deep 100ks ACIS exposure, several deeply embedded X-ray sources are found around OMC 3, two of which coincide with millimeter Class 0 protostars (Tsuboi et al. 2001). This finding may have profound importance for the astrophysics of protostars and possibly the star formation process itself. It strengthens the concept that X-ray ionization is involved in launching bipolar flows and in promoting accretion from the circumstellar disk, both of which are strongest in the Class 0 phase (§4).

3.4. The Galactic Center region

The inner $\approx 100$ pc of the Milky Way Galaxy has a profusion of unusually massive giant molecular clouds with many young OB associations. A $2.6 \times 10^6$ $M_\odot$ black hole resides at the dynamical center, Sgr A*. If viewed from afar, our Galaxy would probably be classified as a mild nuclear starburst galaxy with an extremely weak active galactic nucleus. The configuration of molecular, atomic and ionized gas is extremely confused in the Galactic Center region due both to the increased concentration of matter and the rapidly changing rotation curve.

The Chandra ACIS image of the innermost 20 pc shows a profusion of X-ray binary systems, highly structured dense hot plasma, a bright supernova remnant (Sgr A-East) which may be interacting with Sgr A*, individual young massive stars, and a very weak source with $L_x \approx 2 \times 10^{33}$ erg/s associated with Sgr A* itself (Baganoff et al. 2001). Several of the resolved sources within 1 pc of the nucleus are known Wolf-Rayet stars with estimated masses $> 10$ $M_\odot$, ages up to 5 Myr, and X-ray luminosities of order $10^{33}$ erg/s. But the stellar X-ray emission is dwarfed by Sgr A-East and the diffuse X-ray emission, which may arise from sheared earlier supernova remnants (Maeda et al. 2001).

About 100 pc from the center lies the Sgr B2 giant molecular cloud. Chandra has confirmed the remarkable ASCA finding that the cloud is glowing in
fluorescent Fe Kα 6.4 keV line (Murakami et al., in preparation). This is the first case of an X-ray reflection nebula, and another case is emerging from the Sgr C molecular cloud (Murakami et al. 2001). These molecular clouds glowing in X-rays require that an X-ray source towards the Galactic Center (possibly Sgr A* itself) was bright $\sim 10^2$ yrs ago but has now dimmed. The ACIS image also shows a heavily absorbed faint X-ray source at the center of the cloud and associated with an IRAS source. With $N_H \simeq 9 \times 10^{23}$ cm$^{-2}$ ($A_V \simeq 500$), $kT \simeq 5$ keV and $L_x \simeq 2 \times 10^{33}$ erg/s, it is probably a young stellar cluster somewhat more massive than the Orion Nebula cluster lying on the far side of the cloud. This detection demonstrates Chandra’s capability of finding star forming regions in even the most obscured regions of the Galactic disk.

Figure 3. ACIS-I image of the 30 Doradus region after adaptive smoothing. Features include the bright composite supernova remnant N157B to the southwest, many X-ray binaries, and highly structured large superbubbles surrounding the R136a young stellar cluster. R136a lies within the small central spot, where the emission is dominated by Wolf-Rayet binary systems. Supernova remnants N157C and 1987a lie to the southwest on ACIS-S chips not shown here. From Townsley et al., in preparation.

3.5. The 30 Doradus region

30 Doradus in the Large Magellanic Cloud at $d \simeq 50$ kpc, known optically as the Tarantula Nebula, is one of the few young ‘super star clusters’ in the Local Group of Galaxies with sufficient mass and concentration to evolve into a globular cluster. The cluster has $> 300$ OB stars, many with masses $> 100$ M$_\odot$, both on the main sequence and in the Wolf-Rayet phase. These massive stars have produced powerful winds and supernova remnants that have ionized a $\simeq 200$ pc region and largely destroyed the parental molecular cloud.
The 25ks ACIS image of 30 Dor is extremely complex (Figure 3, Townsley et al. in preparation; see also Dennerl et al. 2001 for an XMM observation of the region). The dense young stellar cluster R136a at the field center appears as a faint 1"–2" emission region with $L_x \simeq 10^{33}$ erg/s. These many ordinary OB stars are outshined by a dozen individually resolved O3 and WN stars which are known or likely close binaries with masses 80–140 $M_\odot$ lying within 10" of the central cluster. These sources with individual $L_x \sim 3 - 30 \times 10^{33}$ erg/s are likely due to colliding stellar winds. Scattered on scales of tens of parsecs are dozens of X-ray binaries each with $L_x \simeq 10^{33} - 10^{35}$ erg/s. Several arcmins from R136a are three remarkable supernova remnants: N157B, which the Chandra data clearly shows is a composite shell-plus-plerion remnant with a central bright X-ray pulsar; the large shell-like N157C remnant; and SN 1987a.

3.6. Messier 82

The largest scale of star formation known is the starburst galaxy of which M 82 is the closest example at $d \simeq 3.6$ Mpc. The inner kiloparsec of its disk has many super star clusters, each comparable to 30 Doradus, with a net supernova rate around 0.1/yr. Most of these giant OB associations are deeply embedded in dusty clouds so that the reprocessed infrared luminosity exceeds its visual luminosity by a factor of $10^2$. M 82 is a sufficiently bright X-ray source to appear in the UHURU source catalogs 30 years ago. For many years, the nature of its X-ray emission has been debated: the balance between emission from individual supernova remnants, a global hot interstellar medium (known to extend several kpc outward into the halo), OB associations, X-ray binaries, and a putative active galactic nucleus was uncertain. Chandra is resolving these issues for M 82 and other starburst galaxies (Griffiths et al. 2000; Kaaret et al. 2001; Matsumoto et al. 2001; Matsushita et al. 2001; Ward, this conference).

A 35 ks ACIS image shows that 60–75% of the 2–10 keV emission is resolved into compact sources and the remainder arises from diffuse emission or unresolved sources (Griffiths et al. 2000). Several of the ~20 unresolved sources have $L_x > 3 \times 10^{38}$ erg/s, too luminous for neutron star accretion, are likely black holes accreting from the winds of close binary O and Wolf-Rayet companions. While few individual radio supernova remnants are seen in the X-ray image, the global interstellar medium is extremely dense, hot ($T \simeq 40$ MK) and highly structured. Remarkably, its pressure is $10^5$ times that of the hot interstellar medium around the Sun. This interstellar medium probably arises from the early merging of thousand of remnants produced by the starburst, and clearly drives the galactic wind into the halo and intergalactic space. The brightest unobscured super star cluster, M82-A, with optical $L_V \simeq 10^{42}$ erg/s is seen with $L_x \simeq 8 \times 10^{38}$ erg/s. This emission is probably dominated by unresolved X-ray binaries, but the telescope resolution is insufficient to establish the contribution of normal stars or supernova remnants.

3.7. Future prospects

Roughly 1 Ms annually or ~5% of Chandra time is devoted to studies of star formation and young stars. In addition to those outlined above, the program of the first two years includes the following observations:
Nearby low-mass star forming regions  
- R Corona Australis cloud; 
- Lynds 1551 cloud in Taurus; 
- Core A of the Ophiuchus cloud; 
- northern portion of the Chamaeleon I cloud; 
- high-latitude MBM 12 cloud; 
- IC 348 in the Perseus cloud; 
- Herbig-Haro 1-2 region in Orion; 
- TW Hya stars; 
- isolated Herbig Ae/Be stars; 
- MWC 297

High mass star forming regions  
- NGC 2024 and NGC 2068 clusters in Orion; 
- Monoceros R2 cloud; 
- Sharpless 106; 
- W3 B ultracompact HII regions; 
- NGC 3603 young star cluster; 
- Rosette Nebula and molecular cloud; 
- M 16 Eagle Nebula; 
- M 17 Omega Nebula; 
- Sgr C cloud; 
- Galactic Center mosaic; 
- many studies of extragalactic HII regions and star clusters in nearby galaxies

OB and Wolf-Rayet stars  
- τ Sco; δ Ori; λ Ori; τ Ori; HD 206267; ζ Pup; η Carina; γ² Vel; WR 140; WR 147

4. Synthesis of findings

The table below provides a broad-brush summary of the findings outlined above. 

In the nearer star forming regions where molecular clouds are small and few 
high-mass stars, the X-ray luminosity is modest ($L_x \simeq 10^{31} - 10^{33}$ erg/s) and is a 
produced by a combination of magnetic activity in lower-mass stars and stellar 
winds in higher-mass stars. The more distant giant molecular clouds with rich 
high-mass young stellar clusters have X-ray luminosities of order $10^{33} - 10^{36}$ 
erg/s where the principal contributors are Wolf-Rayet stars (binaries?) and 
diffuse emission from individual and merged supernova remnants. In starburst 
environments that involve many molecular clouds and star formation over $10^7$ 
years or longer, the X-ray luminosity is in the range $10^{36} - 10^{41}$ erg/s 
where the emission is mainly produced by X-ray binaries and an interstellar medium 
superheated by many supernova remnants. 

The X-ray properties of star forming regions are thus quite complex. When 
the star formation rate is high enough to produce many OB stars, star birth 
and star death are spatially intertwined. But in these massive star forming 
regions, the X-ray emission from the death phases (supernova remnants, X-ray 
binaries) typically outshine the emission from the birth phases (proto star, 
T Tauri, Herbig Ae/Be, OB stars) by a large factor. Pre-main sequence and OB 
stellar X-ray emission is undoubtedly present at low levels in many fields of 
supernova remnants and starburst regions.

5. Astrophysical issues

A wide range of astrophysical issues arise from X-ray studies of young stars and 
star forming regions. Some involve the mechanisms of X-ray emission: Exactly 
how do OB winds produce X-rays? Do low-mass pre-main sequence stellar mag- 
netic fields arise from a dynamo, as in the Sun, or in other ways? Are protostellar 
X-rays produced in solar-type magnetic fields rooted in the stellar surface, or in 
field lines reaching from the star to the disk? 

But the implications of young stellar X-ray emission that may have the 
most profound implications involve the ionization effects of the X-rays on am- 
bient molecular material (Glassgold et al. 2000). X-ray energy is typically de- 
positioned at column densities around $10^{21} < \log N_H < 10^{23}$ cm$^{-2}$ from the source.
Thus every embedded protostar, T Tauri star and OB star will produce an X-ray dissociation region (XDRs) of low-ionization fraction (Hollenbach & Tielens 1997). These are have much lower ionization fraction but extend to larger distances than Stromgren spheres and photodissociation regions around embedded OB stars. X-ray ionization will dominate over cosmic ray ionization that is thought to uniformly permeate molecular clouds: these XDRs may extend $10^{-2}$ pc around typical T Tauri stars and $10^0$ pc around X-ray-luminous OB stars (Lorenzani & Palla 2001; these are shown as grey regions in Figure 1). Elevated ionization of largely neutral molecular gas will increase the coupling between the gas and magnetic fields by slowing ambipolar diffuse. This may have a critical inhibiting effect on future star formation; see Bertoldi & McKee (1996) for the theory of photoionization self-regulation of star formation.

On smaller scales, X-ray ionization is definitely likely to be the principal ionization source within protostellar systems. X-ray ionization can penetrate deeply into circumstellar disks, stimulating MHD instabilities and accretion, and is probably important for the coupling between disks and bipolar outflows (Glassgold et al. 2000).

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