X-RAYS FROM STAR-FORMING REGIONS: NEW OBJECTS, NEW PHYSICS, NEW VISIONS

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Abstract

Star-forming regions have been the targets of X-ray observations since the dawn of satellite X-ray astronomy. The increase in sensitivity and/or spatial resolution offered by XMM-Newton and Chandra allows a dramatic improvement, both qualitative and quantitative, on our knowledge of high-energy phenomena in these regions and the underlying physical processes. We summarize here some recent developments: the Orion Nebula Cluster and its 1000+ stellar X-ray sources; Herbig-Haro objects and their high-speed shocks; protostars, brown dwarfs and their unusual magnetic activity; and the discovery of diffuse X-ray emission from HII regions, presumably related to strong winds from massive stars. The role that future X-ray missions may play in the field is already starting to be visible.

Key words: Missions: XMM-Newton, Chandra; Orion, HH objects, protostars, brown dwarfs, HII regions, magnetic activity, shocks, irradiation, diffuse X-ray emission

1. Introduction: An Old New Topic

Star-forming regions have been known to be associated with X-ray emission for over 30 years, beginning with the discovery of an extended source coincident with the Orion Nebula (M42) using the Uhuru ANS and SAS-3 satellites (Den Boggende et al. 1978, Bradt & Kelley 1979). Possibilities to produce X-rays from star forming regions include magnetic activity from lower mass pre-main sequence stars; thermalization of the high velocity winds of higher mass OB stars, either close to the star or where at a wind termination shock; and supernova remnants from past generations of OB stars (Figure 1). It took the advent of the first imaging X-ray satellite, the Einstein Observatory, to realize that stars were the “true” X-ray emitters in the Orion Nebula. Progress was rapid from the start, owing to the large field-of-view, 1 sq. deg. or more for satellites such as Einstein and ROSAT, allowing to detect dozens of stellar sources in a single exposure of nearby star forming regions (see review by Feigelson & Montmerle 1999, henceforth FM).

In parallel with the development of X-ray satellites, major progress was being achieved in sensitive solid-state detectors for ground-based telescopes in the IR and mm ranges. This led to the discovery of circumstellar material, accretion disks and envelopes around young stars and protostars (see, e.g., André & Montmerle 1994). High-angular resolution imaging, by, e.g., the Hubble Space Telescope and mm interferometers, showed that young stars and protostars (“Young Stellar Objects”: YSOs) lose mass in the form of jets and outflows, collimated perpendicular to the circumstellar disks. Thus accretion and ejection are currently viewed as correlated phenomena, somewhat paradoxically required to build up a star. Fig. 2 gives a spectacular example, obtained with the Hubble Space Telescope, of a disk-jet system associated with a very young star.

It is widely believed that magnetic fields are required to explain, and perhaps even cause, the ejection of material, from the disk, and/or from the central, growing star (e.g., Königl & Pudritz 2000). Fig. 3 illustrates various star-disk magnetic configurations from the literature.

Figure 1. Diagram of the expected X-ray components from a giant molecular cloud with a blister HII region, embedded young star clusters and distributed star formation. Symbols: ⋆ = OB stars; ○ = Herbig Ae/Be stars; ● = T Tauri stars; + = protostars; squares = X-ray binary system. The hatched region outside of the cloud represents a supernova remnant, and shaded regions within the cloud represent partially ionized X-ray dissociation regions (see Feigelson 2001).

Figure 2. A spectacular example, obtained with the Hubble Space Telescope, of a disk-jet system associated with a very young star.
2. Activity properties: low-mass young stars

The X-ray properties of T Tauri stars and protostars are now well-known (FM, Imanishi et al. 2001a, Feigelson et al. 2002a), and can be summarized as follows:

- **X-ray luminosities**: $L_X < 10^{28}$ to $10^{31} - 10^{32}$ erg s$^{-1}$; X-ray to bolometric luminosity ratio $L_X/L_{bol} \approx 10^{-4}$.

- **Emission mechanism**: Bremsstrahlung emission from plasmas with $T_X \sim 1 - 10$ keV dominate the X-ray spectra. Emission lines from highly ionized species are clearly present when high-quality spectra are obtained.

- **Ubiquitous flaring activity** on timescales of minutes to days, but more typically $\sim$ a few hours, with amplitudes peak/quiescent flux up to $\sim 100$ (Figure 4).

- **Extinction**: Soft X-ray absorption ranges from negligible to very high for embedded objects like protostars where column densities can be $N_H \sim 10^{23}$ cm$^{-2}$, corresponding to visual absorptions around $A_V \sim 100$.

In addition to X-ray flares, non-thermal radio emission testifies to the existence of $\sim$ MeV electrons (accelerated in flares), radiating via the gyrosynchrotron mechanism, based on flarelike variability, and/or on significant polarization. In contrast, thermal radio emission is attributed to ionized material, either strong winds in the case of T Tauri stars, or hot jets in the case of protostars (FM).

Fig. 5 summarizes the observational properties of YSOs, according to their evolutionary state, from very young ($\approx 10^4$ yrs), envelope-dominated “Class 0” protostars, to evolved ($\approx 10^6 - 10^7$ yrs) “weak-lined” (i.e., diskless) “Class III” T Tauri stars. Note that the most recent results from *Chandra* and *XMM-Newton* have not significantly modified the summary shown in Fig. 5.
The case of protostars deserves some comment. Although the detection of X-ray emission from Class 0 protostars has not been confirmed yet, the X-ray emission from Class I protostars (age \( \approx 10^5 \) yrs) is now widespread, following their announced discovery in the late 90's with ASCA and ROSAT (Koyama et al. 1996, Grosso et al. 1997). However, going back to the Einstein observations of Montmerle et al. (1983), it turns out that a Class I protostar had already been detected (see discussion in Grosso 2001)! The historical point, of course, is that protostars were not known as such at the time, for lack of adequate IR and mm data. Fig. 6 shows, next to each other, the two images of the \( \rho \) Oph cloud from Einstein and from Chandra (from archival data), which are separated by 21 years: the vastly improved angular resolution of Chandra allows accurate identifications of the X-ray sources, but the YLW16A protostar is nevertheless visible on the corresponding Einstein image (circle). Fig. 6 shows the flare-like variability of X-ray sources in the same region, as observed in a \( \sim 100 \) ksec exposure by Chandra (Imanishi et al. 2001a).

3. NEW SATELLITES, NEW OBJECTS

With the advent of a new generation of wide-band (\( \sim 0.2 - 10 \) keV), sensitive X-ray satellites, i.e., Chandra and XMM-Newton, new problems can be addressed, new objects can be detected, and new processes can be studied. We illustrate this by briefly reviewing representative recent results on X-ray emission from YSOs and star-forming regions.

3.1. THE ORION NEBULA CLUSTER

Illuminated by the “Trapezium” OB stars, the Orion Nebula hosts a cluster of 2000+ lower-mass stars called the Orion Nebula Cluster (ONC; Hillenbrand 1997, O’Dell 2000). Fig. 7 (right) shows the first of two \( \sim 40 \) ksec exposures (Garmire et al. 2000). In the 17’ x 17’ field-of-view of the ACIS-I CCD detector lie over 1000 ONC stars, most detectable in the near-IR which can penetrate moderately large column densities (Fig. 8 left). This ACIS image of the ONC is so far the richest X-ray image ever obtained and also contains a wealth of temporal and spectral information.

A variety of findings have emerged so far from the Chandra Orion Nebula studies (Feigelson et al. 2002a & b). Several dozen new YSOs, some in the lightly absorbed
ONC and others deeply embedded in the molecular cores, are discovered. X-ray emission is found to be surprisingly hot \( (T_X > 5 \text{ keV}) \) in a fraction of the low mass pre-main sequence stars, characteristically hotter than those seen in older main sequence stars, and certainly far above the temperatures seen in quiescent solar-like coronae. Curiously, low-mass X-ray emission appears to depend more on stellar mass or luminosity than on rotation, as it does in main sequence stars. The Orion image also provides the largest sample of X-ray detected pre-main sequence brown dwarfs (see below). The majority of sources show prominent flares: solar-mass stars produce flares with \( L_{X, \text{peak}} > 10^{29} \text{ erg s}^{-1} \) roughly once every few days, each lasting 2 to 12 hours. Surprisingly, the \( \sim 30 \text{ M}_\odot \text{ O9.5 star } \theta^2 \text{A Ori} \) exhibited rapid variations also. This is inconsistent with the standard model of production in a myriad small wind shocks and probably requires some near-surface magnetic processes.

### 3.2. Herbig-Haro Objects

During the early fifties, Guillermo Haro and George Herbig independently discovered, associated with dark clouds, tiny luminous spots having “nebular” optical spectra showing sharp emission lines and no continuum. Dubbed “Herbig-Haro objects”, over 500 of these nebulae are now known in star-forming regions (Reipurth & Bally 2001). They are interpreted as ambient cloud material shocked by high-speed (\( \sim 200 - 300 \text{ km s}^{-1} \)) jets powered by protostars and young T Tauri stars (as shown on Fig. 3).

Although an early Einstein study reported the discovery of X-ray emission from HH objects (Pravdo & Marshall 1981), subsequent observations did not confirm it. It is only recently that both Chandra, Pravdo et al. (2001) detected a few X-ray photons from the tip of HH2 (part of the HH1 system) in Orion, while Favata et al. (2002), using XMM-Newton, detected faint X-ray emission from the blue-shifted jet of the L 1551 IRS 5 protostar in Taurus. In both cases the photons are soft, consistent with a shock velocity \( \sim 200 \text{ km s}^{-1} \). Many other HH objects are not seen in X-ray images, presumably due to higher obscuration and/or lower shock temperatures.

### 3.3. Protostars

Whereas only a small fraction of the nearest Class I protostars were detected by ROSAT and ASCA (FM), Chandra and XMM-Newton now detect about 70% of the Class I protostars in nearby YSO clusters (Imanishi et al. 2001a; Getman et al. 2002). The X-ray luminosities and time variability characteristics seem in general very similar to those of T Tauri stars, although protostars tend to have characteristically harder spectra. A remarkable case is the Class I protostar YLW15 in the Ophiuchus cloud, which has been detected on several occasions at both “low” and “high” states, and displayed a \( \sim 20\text{h} \) quasiperiodic sequence of three flares observed by ASCA (Tsuboi et al. 2000). (Unfortunately, it was in its “low” state during Chandra and XMM-Newton observations.) The case of the youngest, Class 0 protostars is less clear, with tentative detections in Chandra images of the OMC 2/3 clouds in Orion (Tsuboi et al. 2001) but no further detection in several nearby clouds so far.

### 3.4. Brown dwarfs

At the lowest end of the stellar mass function, brown dwarfs are especially interesting since their effective tem-
perature is so low (<3000 K) that their photospheres have a very low ionization degree. X-ray emission from brown dwarfs was first discovered by ROSAT in the Chamaeleon and other nearby clouds (Neuhäuser & Comerón 1999). Using Chandra, Feigelson et al. (2002a) detected 30 very low mass objects in the ONC, and smaller samples are seen in IC 348 and Ophiuchus (Preibisch & Zinnecker 2001, 2002; Inamishi et al. 2001b). This now large sample of pre-main sequence very low-mass objects (0.02 < M < 0.1M⊙) is characterized by strong surface magnetic activity very similar to those of late-type stars, with Lx/Lbol ≈ 10⁻³ at the saturation level, hard spectra, and flares. In contrast, only one old brown dwarf (~500 Myr) has been identified by Chandra so far while flaring (Rutledge et al. 2000).

3.5. Diffuse emission from HII regions

Evidence for diffuse X-ray emission has been found for the first time in HII regions by Townsley et al. (2002, in preparation), i.e., in the Rosette Nebula. Powered by the OB association NGC 2244, this thick shell-like blister HII region lies on the edge of a giant molecular cloud at a distance of 1.4 kpc, and contains two early O stars plus several late O and early B stars. The radio HII region and visible band nebula exhibit a large central cavity, ~10 pc in diameter. As depicted in Fig. 8, the new Chandra study shows that this cavity contains X-ray emitting plasma.

The high-resolution mirrors of Chandra are critical for resolving the diffuse emission from the ~350 faint stellar sources. A spectral fit to the diffuse emission obtained (after removal of the instrumental background, point sources and detector charge transfer inefficiency effects) are consistent with an absorbed Raymond-Smith plasma N_H = 7 × 10^{21} cm⁻², kT = 0.6 keV and Lx ≈ 8 × 10^{32} erg s⁻¹ in the 0.5–2 keV band after correction for absorption. Based on the X-ray luminosity function (XLF) found by Chandra in the ONC (see above), Townsley et al. estimate that the unresolved point source population (made up of faint, low-mass stars) should not be contributing more than to 25% of this emission. As outlined below, this nebulous X-ray emission in the Rosette Nebula, and an even more dramatic case found very recently in the M17 HII region, is best explained as the result of collisions and shocks between OB stellar winds and the ambient cooler medium (Townsley et al., in preparation).

4. New physics

4.1. Coronal activity and star-disk interactions

X-rays from pre-main sequence low-mass stars, as in the Sun and other older late-type stars, are most easily interpreted as emission from plasma heated and confined by multipolar magnetic fields rooted in the stellar surface (FM). The most convincing arguments are based on the flaring activity. However, it has proved difficult to establish the properties of these flares with any confidence. While X-ray flares from T Tauri stars had often been modeled as uniform plasma in very large (l > R⋆) magnetic loops undergoing radiative cooling, it is possible that many flares arise in smaller, complex loop arcades which reconnect and reheat the plasma on timescales of hours. The inferred emitting volume is then considerably reduced compared to that implied by pure radiative cooling (Favata et al. 2001). In the one case where a T Tauri star is sufficiently bright to give a good high-resolution Chandra grating spectrum, TW Hya, the situation is even more confusing with plasma densities inferred from helium-like triplet lines (see Porquet et al. 2001) much higher than those seen in any normal stellar flare (Kastner et al. 2001).

The real issue, however, is whether magnetic configurations other than solar may exist. The younger YSOs (from Class 0 to Class II) are surrounded by accretion disks, which are widely thought to harbor magnetic fields, originally interstellar and dragged by gravitational collapse, perhaps amplified by an intra-disk dynamo as well. While the exact configuration is still debated, all models agree that, in order to provide a satisfactory framework to drive jets and outflows from accretion, star-disk magnetic struc-
tures must exist (Fig. 3). If some twisting of the field lines is included, resulting for example from shear in the Keplervian disk or fluctuations in the inner accretion disk, flares may occur (Shu et al. 1997). This situation has been numerically studied by Hayashi et al. (1996), assuming some finite resistivity for the field lines: in brief, powerful flares with X-ray emitting plasma and “coronal mass ejections” are produced at the star-disk corotation radius. This situation may have already been observed in the triple X-ray flare of YLW 15 (Tsuboi et al. 2000). Montmerle et al. (2000) propose that three ~ 20h successive reconnection events occurred in a star-disk magnetic configuration, in which the protostellar rotation is very rapid and not yet decelerated by interaction with the disk.

The X-ray emission from brown dwarfs also presents new challenges in coronal physics. Despite their similarities with late-type stars, there is clear evidence from Hα surveys of older L- and T-type brown dwarfs in the solar neighborhood that their chromospheric and coronal activity drop at the stellar/sub-stellar boundary (e.g. Gizis et al. 2000). This is probably related to the fact that these very cool objects ($T_{\text{eff}} < 3000$ K) have essentially neutral atmospheres with high electrical resistivity, in which the rapid decay of currents prevents the buildup of magnetic free energy and therefore cannot provide support for magnetically heated chromospheres and coronae. However the very low-mass stars for which quiescent X-ray emission was detected are all very young, and their atmosphere is still warm enough to be partially ionized and therefore capable of sustaining electrical currents. The transient coronal plasma, which gives rise to the observed X-ray flare in old very low mass stars, could be created by buoyant flux tubes that are generated in the interior and rise rapidly through the atmosphere, dissipating their associated currents in the upper atmospheric layers (Fleming et al. 2000; Mohanty et al. 2002).

4.2. Which dynamo?

Another significant puzzle is the weakness or absence of a statistical correlation between X-ray emission and stellar rotation in T Tauri stars compared to the very strong relation seen in main sequence stars. The problem is most dramatic in the new Chandra ONC dataset where over 200 well-characterized pre-main sequence stars can be placed on the $L_X - P_{\text{rot}}$ diagram (Feigelson et al., in preparation). A random scatter diagram rather than a tight correlation is seen: mass rather than rotation appears to be principal determinant of X-ray activity.

The reasons for this are not at all clear. One possibility is, as discussed just above, that the X-ray flares arise from disk-related magnetic fields rather than solar-like fields. But X-ray properties seem remarkably insensitive to the presence or absence of an infrared disk. Another possibility is that we are seeing the effects of a different magnetic dynamo in the interiors of YSOs. Main sequence stellar activity is attributed to an $\alpha - \Omega$ dynamo where the fields are generated at the boundary between the convective and radiative zones. But T Tauri stars are nearly fully convective, and their magnetic fields may be generated entirely within the convective zone ($\alpha^2$ or turbulent dynamos). Here the relationship between surface rotation and magnetic fields may break down (Kuker & Stix 2002).

4.3. Disk irradiation by X-rays and particles

The question of star-disk vs. star-star magnetic topology is of importance not only for magnetohydrodynamical aspects of flare and outflow physics, but also for key issues relevant to the earliest stages of the evolution of protoplanetary disks. We outline three aspects of this complex issue.

- **X-ray ionization effects.** X-ray flares must impact some part of the circumstellar disks and partially ionize the largely neutral material. The uncertain geometry of the X-ray emitting magnetic structures controls the size of the portion of the disk that will be irradiated. With reasonable X-ray luminosities and optimistic geometries, Igea & Glassgold (1999) have shown that X-ray ionization (generally low, $n_e/n_H < 10^{-7}$) will induce the MHD magneto-rotational (Balbus-Hawley) instability, which in turn stimulates turbulent viscosity and promotes accretion onto the young star. Ionization of the outer layers of the disk may be critical for coupling the Keplerian rotation of disk material to the collimated outflows (Ouyed & Pudritz 1999).

- **Spallation by MeV particles.** As already mentioned, in addition to voluminous X-ray results on YSO flaring, radio continuum studies show that, as in solar flares, MeV electrons are copiously produced in (at least some) YSO
flares (FM). MeV protons are also probably accelerated in these violent magnetic reconnection events. An estimate of this effect for \( \simeq 1 \, M_\odot \) YSO analogs of the young Sun in the Chandra observation of the ONC indicates a 10\(^3\)-fold enhancement in energetic protons compared to contemporary levels (Feigelson et al. 2002b).

This result may have profound implications for a long-standing puzzle in the meteoritic record of conditions in the protoplanetary disk around the early Sun (Feigelson et al. 2002b). Anomalously high levels of daughter products of several radioactive nuclei with short lifetimes (e.g. \(^{41}\)Ca, \(^{26}\)Al, \(^{53}\)Mn) are found in calcium-aluminum-rich inclusions of carbonaceous chondrites such as the Allende and Murchison meteorites. These have traditionally been attributed to the injection of recently synthesized nuclides by a supernova remnant near the molecular cloud that formed our solar system. However, the 10\(^5\) elevation in MeV protons inferred from the Chandra data is just the level found in recent calculation of radioisotope production by spallation of disk solids. X-ray astronomy thus provides a novel bridge for the study of the origins of our solar system.

- **The neutral Fe 6.4 keV fluorescence line.** In a fashion inspired from AGN studies (e.g. Nayakshin & Kazanas 2002), one can look for neutral Fe K\(\alpha\) line emission at 6.4keV, in addition to the 6.7keV emission line from the flare plasma, resulting from the fluorescence of the accretion disk induced by the flare X-ray irradiation. A strong double-line feature may imply that the X-ray emitting plasma is located high above the disk in a “lamppost” configuration which would lead to efficient ionization and spallation in the disk (see Fig. 1). This double-Fe line spectral signature has been seen to date during flares of two protostellar X-ray sources (Koyama et al. 1996, Imanishi et al. 2001a). In principle, if sufficient signal over many hours could be obtained, the X-ray/disk geometry could be revealed by reverberation mapping.

- **Disk chemistry.** While the chemistry of YSOs disks had been long studied in the context of the solar nebula and formation of our planetary system, advanced in millimeter and infrared imaging and spectroscopy is providing many new insights. Among them are hints of chemical effects attributable to X-ray irradiation. Calculations indicate that X-rays should significant heat the gas above the dust temperature by hundreds of degrees in the outer layers of the disk, altering the chemistry and expected molecular spectroscopic signature (Glassgold & Najita 2001). Kastner et al. (1997) attributed the high CN/HCN ratio and high HCO\(^+\) abundance in the disk of TW Hya to X-ray illumination. Similarly, the outer disk of LkH\(\alpha\) 15 shows a 1–3 order of magnitude excess of HCN and CN compared to chemical models, which might be explained by X-ray ionization and dissociation which promotes transformation of CO into cyanides (Aikawa et al. 2002).

### 4.4. Shock Physics

Up to now, X-ray emission in young stellar objects has been discussed principally in the context of magnetic activity. However, as more sensitive observations become possible, new, weaker processes become accessible, like interstellar shocks (Fig. 1). Since X-ray emission results from the thermalization of shocked gas flowing at velocity \( v_s \), the approximate temperature \( T_X \) of a strong, adiabatic shock, can be found from \( T_X = (3/16k)\mu m_p v_s^2 \): \( T_X \sim 10^6 \) K for \( v_s \sim 200-300 \) km s\(^{-1}\) and \( T_X \sim 10^7 \) K for \( v_s \sim 1000 \) km s\(^{-1}\). We thus expect soft X-ray production associated with accretion flows and Herbig-Haro outflows from low-mass YSOs, and hard X-rays associated with the winds of massive stars. Study of these processes presents considerable observational difficulties, first due to the absorption of soft X-rays by line-of-sight material and second due to the difficulty in resolving truly diffuse emission from unresolved stellar emission in rich YSO clusters.

However, three lines of recent evidence point to such processes. First, according to Kastner et al. (2002), high-resolution Chandra/HETGS spectroscopy of the nearest and brightest classical T Tauri star, TW Hya, indicates the dominant plasma is cooler (\( T_X = 3 \times 10^6 \) K) and denser (\( n_e \approx 10^{13} \) cm\(^{-3}\)) than usual flare plasmas, and further shows large abundance anomalies. Such characteristics are consistent with a shock from mass being accreted at a velocity \( \approx 200 \) km s\(^{-1}\) and at a relatively high rate \( M \sim 10^{-8} M_\odot \) yr\(^{-1}\), although the abundance anomalies are more consistent with a surface flare model.

Second, the detection of soft X-rays from HH-2 (Pravdo et al. 2001) is a very promising of shock emission. It is interpreted as hot spots at \( \sim 10^6 \) K resulting from the collision of the \( \sim 250 \) km s\(^{-1}\) jet with the ambient interstellar medium. Discussing the case of L1551, Favata et al. (2002) raise interesting astrophysical issues such as X-ray ionization on ambient cold gas, leading to an enhanced coupling of matter with magnetic fields.

The third case of energetic shock processes in star formation regions is clearly indicated by the discovery of diffuse X-rays in rich OB associations like Rosette and M 17 (Townesley et al., in preparation). Several percent of the radiative luminosity in the earliest O stars is converted into wind mechanical luminosity with mass-loss (\( M > 10^{-6} M_\odot \) yr\(^{-1}\)) and \( L_W \sim 1/2 \dot{M} v_w^2 \sim 10^{36} - 10^{37} \) erg s\(^{-1}\). A naive estimate shows that the thermalization of the wind should yield post-shock temperatures \( \sim 1-5 \) keV (Weaver et al. 1997). A closer look at the interaction between the winds and the surrounding HII region shows however that the problem is quite complex, and is still not resolved theoretically 35 years after the discovery of stellar winds from early-type stars. For example, it has long been recognized that the Rosette Nebula is much smaller than expected from a wind-blown bubble with an age of a few \( 10^6 \) yrs (Oey 1996; Bruhweiler et al. 2002).
Several physical effects may complicate the thermal structure of the wind shock and account for the age-size discrepancy: dissipation in a turbulent mixing layer between an ionization-bounded HII layer and a hot shocked stellar wind (Kahn & Breitschwerdt 1990); non-local conductive electron transport, leading to nonthermal hard X-ray emission (Dorland & Montmerle 1987); and mass loading of the stellar winds with interstellar material, heating the flow near the stars and weakening the terminal shock (Pittard, Hartquist, & Dyson 2001 and refs therein). Hydrodynamical calculations of X-ray emission for two cases of OB wind-blown bubbles (Strickland & Stevens 1998; Cantó, et al. 2000) predict emission to several keV in the parsec-scale wind collision zones between the principal O stars in the association. So while we have long been expecting diffuse X-ray emission from HII regions, the possible interpretations of the data at hand are diverse, and the work in progress by Townsley et al. should shed a fresh light on the new physics of the interaction of massive stars with their environment.

5. Conclusions

As in other fields of X-ray astronomy, *Chandra* and XMM-Newton have opened a new era for the study of star-forming regions and the early stages of stellar evolution. This era is only starting, since at the time of this Conference only a limited amount of results are available. However, the selection we have presented above already demonstrate the new possibilities:

- In dense young clusters, like the ONC, several hundreds of low-mass stars can be detected and identified simultaneously in one image, from massive OB stars down to substellar objects which will evolve into brown dwarfs.
- Protostars are detected with a high efficiency. Most detected protostars are Class I (evolved, age \( \sim 10^5 \) yrs), along with two candidate Class 0 (young, age \( \sim 10^4 \) yrs);
- X-ray flares testify to the intense magnetic activity (stellar surface or star-disk reconnection events) of YSOs, and provide a unique probe of magnetic fields associated with the “central engine” powering jets and outflows;
- X-ray activity, down to very low levels, has an important impact (via irradiation processes) on physical conditions in protoplanetary disks, in particular ionization and coupling of material with magnetic fields, and by inference on the early solar system where products of internal spallation reactions may be recorded today in anomalous meteoritic abundances;
- The increase in sensitivity and/or angular resolution has enlarged the number of observable mechanisms for YSO X-ray emission, to include shocks (both from accretion in T Tauri stars, and from jets in Herbig-Haro objects), and shock-related pc-scale diffuse emission processes from stellar winds of massive stars in HII regions.

At the same time, the limitations of *Chandra* and XMM-Newton already begin to be visible: for instance, high-resolution spectroscopy at 6.4 keV ($\Delta E << 100$ eV), combined with a higher throughput to allow time resolution, is necessary to use “reverberation mapping” to probe the circumstellar disks of YSOs. So, even as *Chandra* and XMM-Newton results on star-forming regions keep coming, it is already time to follow the next-generation X-ray projects like Astro-E II, XEUS and Constellation-X!

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