X-ray insights into star and planet formation

Eric D. Feigelson[1]

Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802

Edited by Harvey D. Tananbaum, Smithsonian Astrophysical Observatory, Cambridge, MA, and approved February 5, 2010 (received for review December 3, 2009)

Although stars and planets form in cold environments, X-rays are produced in abundance by young stars. This review examines the implications of stellar X-rays for star and planet formation studies, highlighting the contributions of NASA's (National Aeronautics and Space Administration) Chandra X-ray Observatory. Seven topics are covered: X-rays from protostellar outflow shocks, X-rays from the youngest protostars, the stellar initial mass function, the structure of young stellar clusters, the fate of massive stellar winds, X-ray irradiation of protoplanetary disks, and X-ray flare effects on ancient meteorites. Chandra observations of star-forming regions often show dramatic star clusters, powerful magnetic reconnection flares, and parsec-scale diffuse plasma. X-ray selected samples of premain sequence stars significantly advance studies of star cluster formation, the stellar initial mass function, triggered star-formation processes, and protoplanetary disk evolution. Although X-rays themselves may not play a critical role in the physics of star formation, they likely have important effects on protoplanetary disks by heating and ionizing disk gases.

massive stars | planet formation | premain sequence stars | star formation | x-ray astronomy

Thermodynamically, X-ray astronomy should have little to say concerning the origin of stars and planets which form in molecular clouds around $T \sim 10$ K and protoplanetary disks around $T \sim 100$–$1,000$ K, respectively. It was thus unclear why the Orion nebula was found to be a spatially resolved source by early X-ray observatories (1). The answers began emerging with the focusing optics of the Einstein Observatory: Massive stars produce X-rays in their radiatively accelerated winds, and low-mass premain sequence (PMS) stars produce powerful magnetic reconnection flares (2, 3). Diffuse X-ray emission attributed to past supernova explosions was also seen in the most violent starburst regions (4).

While progress was made in understanding these processes with the ROSAT and ASCA (Advanced Satellite for Cosmology and Astrophysics) observatories during the 1990s (5), the Chandra X-ray Observatory provided uniquely spectacular views of star-forming regions in X-rays. The subarcsecond imaging of the Chandra mirrors is needed to resolve crowded young stellar clusters (YSCs), and the four dimensions of data (right ascension, declination, energy, and arrival time for each photon) from the Advanced CCD Imaging Spectrometer (ACIS) characterize the emission processes (6, 7). Fig. 1 shows two ACIS images of nearby star-forming regions, one a typical YSC with hundreds of X-ray sources associated with PMS stars, and the other a richer YSC with thousands of X-ray stars and diffuse emission from shocked massive winds outflowing into the galactic interstellar medium.

The decades witnessing these X-ray findings were also critical in advancing our understanding of star-formation processes. It became evident that star formation is far more complex than gravitational collapse of a spherical, quiescent cloud of cold gas via the Jeans instability. Galactic molecular clouds are in a dynamical state of supersonic magnetohydrodynamical turbulence, and gravitational collapse is impeded by angular momentum and magnetic pressure as well as thermal pressure. Excess angular momentum explains the prevalence of binary companions and infrared-emitting circumstellar disks around protostars. These disks are the sites of planet formation, and discoveries of exoplanets show that planetary systems are very common. Some aspects of star formation that are still poorly understood, particularly involving the birth of rich star clusters, will benefit from X-ray studies. X-ray irradiation of protoplanètary disks are very likely to have significant effects on disk physics and chemistry, and may be an important influence on the processes of planet formation.

We address here seven topics where X-ray studies have had value, or show promising opportunity, for addressing issues arising in star and planet formation studies. The review is not comprehensive and much of the relevant research, both observational and theoretical, is still in progress. Other important topics include characterizing accretion shocks in PMS stars (8) and studying local templates for starburst galaxies (9).

Discussion

X-Rays from Protostellar Outflow Shocks. Surveys of molecular and atomic line emission across star-forming regions reveal high-velocity ($v \sim 100$–700 km/s) bipolar outflows produced by the youngest class 0 and class I protostars (10). These are understood as disk material accelerated outward by magneto-centrifugal forces from the inner regions of protoplanetary disks. Collisions with the surrounding interstellar cloud produce shocks which are revealed by a variety of excited atomic and molecular lines; these emission line structures are known as Herbig-Haro (HH) objects. The jets are seen on scales <100 AU (astronomical units) to several parsecs (1 pc $= 3.26$ lightyears), and they sweep up ambient material to produce the bipolar outflows commonly seen in carbon monoxide maps of active star-formation regions. The cumulative kinetic energy of these outflows may be an important source of turbulent energy, helping retard the rate of star formation to its observed low levels.

While previous studies concentrated on gas excited to temperatures $T \sim 10^2$–10^3 K, radiatively efficient shocks at several hundred km/s should produce plasmas at temperatures $T \sim 10^6$ K. Soft X-ray emission from this shock-heated plasma was discovered early in the Chandra mission from a knot of HH 2 far from the host protostar in the Orion molecular cloud (11). X-ray emission was later found from several knots of HH 80-81 in a distant cloud, HH 168 in Cepheus, and a "finger" of the HH 210 outflow from massive protostars in Orion's OMC-1 cloud core. Luminosities ranged from 10^{28} to 10^{31} erg/s but temperatures were always relatively low, around 1–5×10^6 K. Many other HH objects were observed but not detected; their soft X-ray emission is easily absorbed by foreground molecular material. Astrophysical shock models explain the emission in terms of bow and/or internal shocks from the collision of the outflow with cloud gas (12).

Soft X-rays have also been found near the base of several HH outflows (13). The X-ray knot near the base of HH 154 ejected from IRS5 the Taurus L1551 cloud (the host of the first molecular bipolar flow known) exhibited a $v \sim 500$ km/s expansion between Chandra observations in 2001 and 2005 (14). The "beehive" in Orion and other systems show constant soft excess emission

Author contributions: E.D.F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]E-mail: edf@astro.psu.edu.

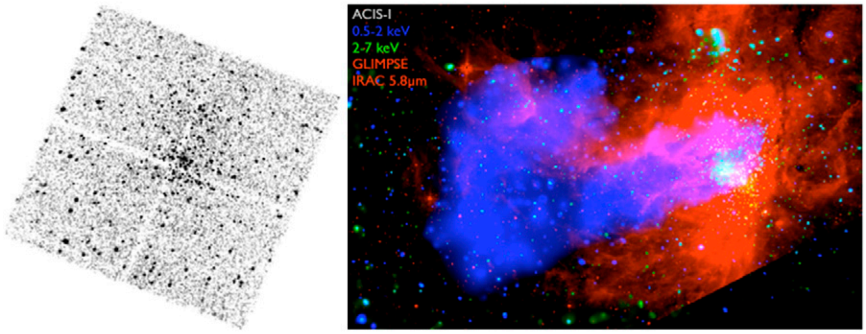

Fig. 1. (*Left*) Chandra ACIS image of the ~5-million-year-old NGC 2362 cluster at a distance of 1.2 kpc (23). (*Right*) X-ray diffuse emission (blue) channeled by cold molecular cloud (red) produced by the rich ~5-million-year-old NGC 6618 cluster (white) in the M 17 star-forming complex (9, 27). Credit: Damiani et al., *A&A*, 460, 133, 2006, reproduced with permission © ESO.

which is spectrally, but not spatially, resolved from the hard flaring emission of the host star. The Class II PMS star DG Tau in Taurus exhibits two X-ray jets; the counterjet shows absorption attributable to gas in the intervening protoplanetary disk (Fig. 2) (15).

X-Rays from the Youngest Protostars. An important, but yet unresolved, question concerns the time that X-ray emission "turns on" in protostars. The earliest stages of stellar evolution are classified by their infrared properties. The class 0 stage, which lasts $\sim 10^4$ years and is seen only in the far-infrared to millimeter bands, is dominated by quasi-spherical infall and formation of a thick protoplanetary disk hundreds of AU in size. The class I stage, which lasts $\sim 10^5$ years, is dominated by near- to far-infrared emission from the accreting protoplanetary disk. Class II PMS stars also have an accreting disk but the stellar photospheres are now visible in the optical band. These are the "classical T Tauri stars" discovered decades ago, and the phase can last from ~0.5 to as long as $\sim 10^6$ years. Class III are the "weak-lined T Tauri stars" where accretion has stopped and the disk is dissipating. Intermediate classes are also known; for instance, there is current interest in "transitional disks" between the class II and III stages when important phases of planet formation likely occur.

The X-ray turn-on question is important because the penetrating X-rays might affect the star-formation process. Theoretically, we expect X-rays to be present from the very beginning, as the magnetic reconnection events producing the X-ray flares depend on an interior magnetic dynamo which should have no delay in operation. X-ray ionization of the class 0 envelope might inhibit collapse by locally increasing the ionization fraction and thereby coupling the mostly neutral gas to magnetic fields. Collapse would then continue anisotropically, on the rapid dynamical timescale along field lines and on the slow ambipolar diffusion timescale across field lines (16). Current protostar collapse models assume a uniform low-level of ionization from galactic cosmic rays and do not account for the possibility of localized ionization from stellar X-rays. X-ray ionization may also be critical closer to the star around the inner disk region where coupling between gas and magnetic fields is needed to propel collimated outflows via magneto-centrifugal acceleration. Virtually all class 0 and I systems exhibit powerful bipolar flows. Calculations of X-ray ionization at the base of protostellar outflows give good agreement with observations (17).

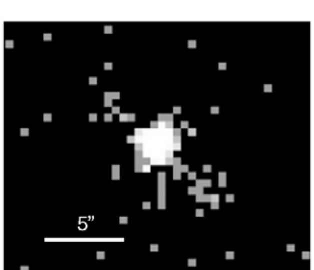

Fig. 2. X-ray jets emerging from the accreting PMS star DG Tau (15). Reproduced by permission of the AAS.

While Chandra regularly detected flares from class I protostars (18), no X-ray emission from class 0 systems has been detected despite intensive searches (19). However, the failure does not mean the X-rays are not present, as the infalling envelopes around class 0 systems have very high column densities which could absorb reasonable levels of X-rays. The youngest systems detected are classified as class 0/I. Chandra resolves the young IRS 7 binary protostar system in the nearby R Corona Australis star-forming cloud; the X-ray emission is variable and heavily absorbed with column density $\log N_H \sim 23.7$ hydrogen atoms cm^{-2} equivalent of $A_V \sim 200$ visual magnitudes of extinction (20). Eight very hard photons, with an implied column density of $\log N_H \sim 24.0\ \mathrm{cm}^{-2}$ are seen from the intermediate-mass Class 0/I protostellar system IRAS 21391 + 5802 in the IC 1396N cloud (21).

Stellar Initial Mass Function. The distribution of stellar masses emerging from the complicated star-formation processes, the stellar initial mass function (IMF), appears to be nearly universal across star-formation regions, open and globular clusters, and the galactic field population. It follows a powerlaw relation at high masses (the Salpeter law), peaks around 0.3 $M_\odot$, and declines towards brown dwarfs. The physical causes underlying this distribution are widely discussed and probably involve the interplay between gravity, turbulence, thermal and magnetic pressures, fragmentation, disk accretion, and star cluster dynamics.

X-ray samples of PMS stars provide an opportunity to measure IMF shapes and spatial distributions, particularly the lower mass regime (typically $0.5 < M < 5\ M_\odot$) in rich YSCs. IMFs can be estimated from X-ray luminosity functions due to a strong, though poorly understood, statistical correlation between X-ray luminosity and mass; $\log L_x = 30.4 + 1.9 \log M$ erg/s over the range $28 < \log L_x < 31$ erg/s and $0.3 < M < 3\ M_\odot$ (22). Masses of X-ray selected PMS stars can be estimated either directly from X-ray luminosities (hard band luminosities are more reliable to reduce obscuration effects), or from the *JHK* color-magnitude diagram. The results for several rich young clusters show general consistency with the standard galactic IMF, though small differences in the lower mass distributions are sometimes present (23, 24).

Structure of Young Stellar Clusters. Practical problems have inhibited observational studies of the PMS stellar populations outside of the nearest ~0.5 kpc. High mass star formation is traditionally located by radio continuum and optical emission line surveys of HII regions in the galactic plane. The luminous massive stars ionizing these regions are often known, but tracing the PMS population is hindered at optical and infrared wavelengths by three problems: diffuse nebular emission from the ionized gas, variable obscuration of stars at different locations in the molecular cloud, and contamination by foreground and background older galactic field stars. Chandra surveys do not substantially suffer from these problems. In particular, Chandra maps typically have ∼10% contamination by field stars in comparison to >10-fold contamination in many near- or midinfrared maps. The reason is that magnetic activity in solar-type stars responsible for the X-ray flaring is high throughout the PMS stages but declines $\sim 10^2$-fold during the first billion years on the main sequence (25).

A benefit of the selectivity of Chandra X-ray samples for PMS stars is the opportunity to study the spatial distribution of young stars and star formation under a variety of star-forming conditions. As expected from infrared studies (26), many PMS populations are dominated by the rich YSCs which ionize HII regions. These clusters have hundreds or thousands of members with roughly spherical distributions. Fig. 1 shows two examples, NGC 2362 and central NGC 6618 cluster in M 17 (23, 27). Less populous YSCs are often seen still embedded in molecular clouds adjacent to HII regions. They can have clumpy structures, as seen in the obscured regions of the M 17 cloud. The W 3 complex has three HII complexes with different morphologies: W 3 Main is a rich spherical cluster, W 3(OH) is less rich with clumpy substructure, and W 3 North is an isolated O star without associated PMS stars (28).

A major result of both infrared and X-ray studies of rich YSCs is the presence of triggered star formation on the peripheries of their expanding HII regions. The nearby giant HII region IC 1396 ionized by the Trumpler 37 cluster is an excellent laboratory for small-scale triggered star formation in bright-rimmed cloudlets. Chandra study shows that the IC 1396N cloudlet has produced about 30 stars with ages spanning class I to III; a clear spatial gradient in star ages is seen consistent with the ablation of the cloud over several million years (21). The Cepheus B molecular cloud core on the edge of the Cep OB3b YSC has produced a richer triggered cluster, again spread over several million years (29). The Rosette nebula's NGC 2244 has triggered substantial satellite clusters, both in the past and today (30).

An important aspect of YSC studies concerns mass segregation, the concentration of massive massive stars in the central regions of rich YSCs. This is a correlation between spatial structure and the IMF. The causes of mass segregation are not well understood: Do massive stars form in regions of high gas density from rapid accretion, or in regions of high protostar density from stellar collisions? Because X-ray images more effectively trace the distribution of lower mass stars, new findings on the effect are emerging. Most rich clusters show mass segregation, but the NGC 2244 cluster illuminating the Rosette nebula has dispersed O stars. Both of its $\sim 40\ M_\odot$ stars are off-center, one isolated and the other with a dense subcluster (24). The obscured W3 Main cluster has a rich older population of PMS stars distributed over several parsecs, and a dense concentration of younger massive stars at the center (28). This is an unusual case where the youth of the massive stars can be established by the small size of their HII regions.

Fate of Massive Stellar Winds. The radiatively accelerated winds of massive stars have been known for several decades, but only close to the star where their broad emission and absorption lines can be studied in the ultraviolet and X-ray bands. At greater distances, their emission disappears from any band although the collective effects of their winds on large scales are important for energizing and enriching the galactic interstellar medium. The long-standing prediction of powerful hard X-ray emission from the terminal shocks of winds from young massive stars colliding with surrounding molecular clouds (31) was not validated by early X-ray observations.

Chandra has now clearly discovered the large-scale shocked massive winds in a few YSCs. The most dramatic case is M 17, where 10^6 K plasma fills the HII regions and streams outward into the galaxy through a broad channel in the cold molecular cloud shown as the blue plume in Fig. 1 (9, 32). As the emission appears center-filled rather than edge-brightened, it likely arises from the low-density shocks of the winds from several dozen massive stars rather than from terminal shocks where they interact with the molecular cloud. The absence of strong terminal shock emission, particularly in embedded ultracompact HII regions, requires explanations such as entrainment of the winds by colder gas and/or a fractal structure of the surrounding cloud gas.

The empirical study of diffuse X-ray plasma around rich YSCs is difficult for several reasons: the emission has low surface brightness so that instrumental background subtraction is important; the emission is soft and can be easily obscured by intervening interstellar gas; and the emission from thousands of low-mass PMS stars can masquerade as diffuse plasma emission. As a result, the detection of diffuse X-rays from HII regions, including reports of a hard nonthermal component, is uncertain in some cases.

Despite these difficulties, the results to date strongly suggest that the traditional view of HII regions as "Strömgren spheres" filled with $\sim 10,000$ K gas (with some clumping factor) is often incorrect. This gas at intermediate temperatures responsible for optical HII region emission lines is, at least in some cases, restricted to a thin "Strömgren shell" and most of the volume is filled with low-density 10^7 K shocked wind plasma.

X-Ray Irradiation of Protoplanetary Disks. There is increasing recognition that the circumstellar disks around PMS stars where planetary systems form are irradiated by light from the host stars. Photospheric radiation is important for heating the outer disk layers and causing them to puff upwards away from the midplane; this effect is necessary to explain the flat midinfrared spectrum of class I and II PMS stars (33). It is therefore natural to expect that X-rays produced in magnetic loops above the stellar

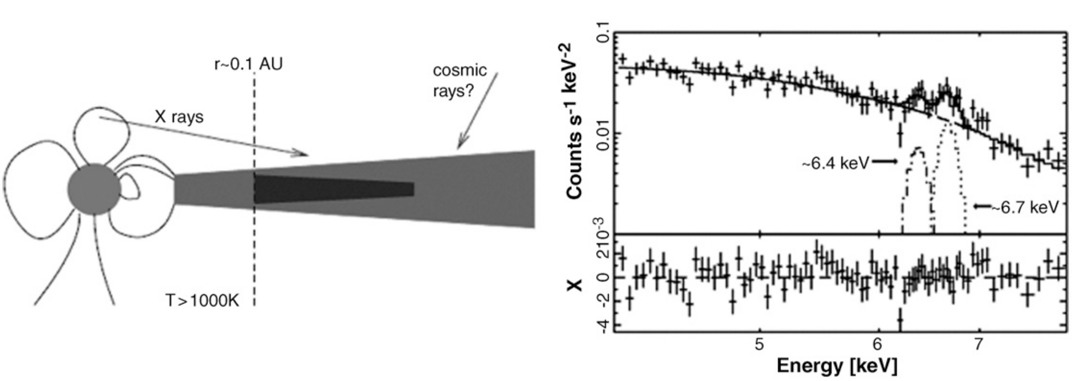

Fig. 3. (*Left*) Diagram of the irradiation of a planet-forming disk by flare X-rays from the host premain sequence star (36). (*Right*) Chandra ACIS spectrum of the protostar YLW 16A in the Ophiuchus cloud ($d \sim 140$ pc) showing the 6.4 keV fluorescent line from irradiation of cold gas, likely arising from the protoplanetary disk (18). Credit: Güdel et al., *A&A*, 478, 797, 2008, reproduced with permission © ESO.

surface will also illuminate the disks, as illustrated in Fig. 3 (*left*). A considerable body of theoretical calculations have been made on the effects of PMS X-rays on disk thermodynamics, structure, dynamics, and chemistry (see reviews by refs. 34–38). Calculations indicate that X-rays will be the dominant source of ionization in the outer disk layers, stimulating ion-molecular chemical reactions, desorbing molecules from grain surfaces, heating the gas (but not dust) to several thousand degrees, and photoevaporating the disk gases towards the end of the disk lifetime.

One of the most important implications of X-ray ionization is the induction of the magneto-rotational instability. Normally considered in fully ionized plasmas, it will operate in largely neutral shearing flows if the ionization fraction exceeds $\sim 10^{-12}$. In a Keplerian disk, this instability quickly results in full magnetohydrodynamical turbulence (37). A turbulent protoplanetary disk has many important consequences such as promoting accretion onto the PMS host star through increased viscosity, inhibiting settling of very small solid particles towards the midplane, concentrating very small solids in temporary turbulent eddies, reducing the inspiral of small solids due to headwind effects, and reducing the inward type I migration of larger protoplanets. While the outer layers of the disk will always be partially ionized by PMS X-rays, the effect on planet formation processes depends on whether this ionization penetrates towards the midplane. This in turn depends on the spectrum of the incident X-rays; in cases where the PMS flaring is unusually luminous, the plasma temperature can exceed ∼200 million K (39). In such cases, the turbulent region may reach the midplane over much of the disk, while in cases with less penetrating X-rays, a substantial "dead zone" of nonturbulent gas is expected.

Chandra studies provide two lines of observational evidence that the stellar X-rays do efficiently irradiate protoplanetary disks. First, the 6.4 keV fluorescent line of neutral iron is seen in a small fraction of PMS X-ray sources, particularly the very young class I protostars with heavy disks. The best example of this fluorescent line emission is shown in Fig. 3 (*right*) (18). The measured soft X-ray absorption requires that fluorescing material does not lie along the line of sight, so a disk-like geometry is favored. A midinfrared [NeII] emission line is also seen in some protoplanetary disks and can be attributed to X-ray irradiation (40). Second, in a small study of PMS stars where the disk inclinations are independently measured in Hubble Space Telescope images, highly inclined disks show more soft X-ray absorption than stars with face-on disks (41).

X-Ray Flares and Ancient Meteorites. A fascinating approach to the challenges of planet formation is the study of ancient meteorites which recently impacted Earth from disturbances in their long-lived orbits in the Asteroid Belt. The meteorites are remnants of the protoplanetary disk and thereby reveal stages in the growth of planetesimals during the PMS stages of the Sun's protoplanetary disk starting 4.567 billion years ago (42). Two characteristics of stony meteorites have been particularly puzzling for decades, and may have explanations linked to the X-ray flares seen in Chandra observations of PMS stars.

First, a large fraction of the mass of stony meteorites are in the form of chondrules, millimeter-sized globules of flash-melted rock. Simple models of protoplanetary disks cannot explain the sudden melting of these solids and a variety of explanations have been invoked: protoplanet-induced spiral shocks; protoplanet-induced supersonic bow shocks; lightening; and magnetic reconnection events (43). The prevalence of X-ray flares seen in PMS systems provides an empirical basis for this last possibility. Two models have been proposed: direct melting of prechondrule dustballs by X-ray and ultraviolet radiation in the magnetosphere of the PMS Sun (44), and indirect melting of dustballs in the disk by the shock expected to accompany X-ray flares analogous to solar coronal mass ejections following solar flares (45). Each of these models has additional restrictions; in the former, the chondrules must be lofted by outflows from the Sun's vicinity and deposited in the Asteroid Belt, while in the latter, the dustballs must be lofted away from the midplane by turbulence. Neither of these models for the origin of chondrules has been generally accepted, but alternatives also have difficulties.

Second, the most ancient melted rock components—the calcium-aluminum-rich inclusions in carbonaceous chondrites—have very strange isotopic compositions with excess nuclei that are a decay product of short-lived radionuclides like ^{10}Be, ^{26}Al, ^{41}Ca, ^{53}Mn, and (controversially) ^{60}Fe. Some of these parent nuclei are readily produced in supernova remnants and have lifetimes of a million years or longer. These could plausibly be incorporated into the molecular cloud that produced our Solar System from previous generations of star formation. However, this model is implausible for some short-lived radionuclides, particularly ^{10}Be and the possible presence of ^{7}Be (46). These require a spallogenic origin where a proton or helium nucleus with MeV energy impacts a normal nucleus and produces a rare unstable nucleus in a disk solid particle. Solar energetic particles from flares which produce X-rays are known to produce spallogenic isotopes on lunar rocks; however, the abundances of anomalous isotopes in ancient meteoritic inclusions require orders of magnitude excess of energetic particles over contemporary solar levels. Measurement of the flaring intensity and frequency in PMS stars from the Chandra Orion Ultradeep Project (47) gives an estimated 10^5 enhancement in MeV proton production, sufficient to explain some of the important isotopic anomalies (48).

Conclusions

From an astronomical viewpoint, there is no doubt that Chandra studies of star-formation regions provide vivid, often unexpected results. These studies are propelled by both the subarcsecond resolution of the Chandra mirrors and the sensitivity to harder X-rays that can penetrate extinction up to hundreds of visual magnitudes. A rich phenomenology is present in all four dimensions provided by the ACIS detector so that full visualization of the data requires a color movie (49). Chandra has devoted several percent of its observing time to studies of PMS and young massive stars, including seven Large Projects and one Very Large Projects, during its first decade. About 50 refereed studies appear annually relating to Chandra studies of star and planet formation.

There is little doubt that the X-ray selected samples of young stars are beginning to be enormously useful in studies that do not directly relate to the X-ray emission itself. For young stellar populations that are difficult to study in the infrared band due to field star or nebula contamination, or that are sufficiently old that many members have lost their infrared-emitting disks, the X-ray surveys can give the best cluster membership lists. These censuses are needed to study the stellar initial mass function, cluster structure, triggering processes, protoplanetary disk longevities, and star-formation histories of molecular cloud complexes. A particularly valuable synergism between the Cha ndra and Spitzer, NASA's (National Aeronautics and Space Administration) Great Observatory for infrared observations, space missions is emerging. Together they are giving new censuses of PMS stars in a wider variety of star-forming regions (24, 50–58) and are elucidating the evolution of protoplanetary disks and triggered star formation (21, 29, 59).

From an astrophysical viewpoint, it is not yet clear how important X-ray findings will be to our understanding of star and planet formation. X-ray results are only now beginning to be incorporated into our empirical knowledge and theoretical understanding of star-formation processes (60, 61). No convincing evidence has yet emerged that X-rays play an important role in star formation; e.g., by impeding gravitational collapse of gas near X-ray luminous PMS stars due to ambipolar diffusion from enhanced ionization. However, the discovery and elucidation of diffuse X-ray emitting plasma from shocked massive winds is astrophysically important. It not only reveals the supply of energy and gases to the galactic interstellar medium at levels comparable to that of supernova remnants, but also changes our view of HII regions as bubbles filled with 10^7 K rather than 10^4 K gas.

For planet formation, however, it is very likely that X-rays irradiate protoplanetary disks and that the consequent heating and ionization will have a variety of important effects on disk physics and chemistry. It is possible, though far from established today, that X-ray emission plays a critical role in establishing disk turbulence and thereby regulating the formation and early dynamical processes of planet formation. These issues are being studied intensively in theoretical models of turbulent disks and their possible role in planet formation. The magnetic reconnection flares we see with Chandra today may also be responsible for the energetic melting and nucleosynthetic processes on our Sun's protoplanetary disk as revealed by components in ancient meteorites.

ACKNOWLEDGMENTS. E.D.F. thanks his Pennsylvania State University colleagues—P. Broos, G. Garmire, K. Getman, L. Townsley, M. Tsujimoto, and J. Wang—for many valuable discussions and collaborations. This work was supported by National Aeronautics and Space Administration Contract NAS8-38252 and Smithsonian Astrophysical Observatory Contract SV4-74018 (G. Garmire, Principal Investigator), NASA Grant NNX09AC74G, and National Science Foundation Grant AST-0908038.

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