X-RAYS, STAR FORMATION AND THE SOLAR NEBULA

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ABSTRACT. Imaging X-ray satellites have demonstrated that low-mass young stellar objects, from protostars through the zero-age main sequence, exhibit high levels of magnetic activity and flaring. These *in situ* high energy processes may play important roles in star formation and the early history of our solar system. X-ray photoionization of the molecular environment may inhibit gravitational collapse, promote disk-star rotational coupling and disk-outflow interaction. Shocks and protons from flares may be responsible for chondrule melting, excess particle irradiation and isotopic anomalies in meteorites. X-ray surveys also provide insight into the star formation history and efficiency of clouds, the longevity of pre-planetary disks, and the dynamics of star formation.

1. Introduction

Low mass star formation is generally regarded as a low energy process, where the energy per particle is <<MeV and emitted photons have <<keV. It begins with gravitational collapse of an interstellar cloud core with characteristic temperature around 10 K. A protostar is formed with surface perhaps 2000–4000 K with a circumstellar disk typically hundreds of degrees. The star then descends the Hayashi track with spectral type G-K-M to the zero-age main sequence (ZAMS), first interacting with its disk ('classical T Tauri' or CTT phase) and later without an apparent disk ('weak-line T Tauri' or WTT phase). Most of the bolometric emission of young stellar objects (YSOs) thus emerges in the infrared and optical bands. The most energetic component traditionally considered is the CTT wind and Herbig-Haro outflow, where velocities reach 300 km/s and emission line temperatures of 10^4 K. Early stellar evolution is reviewed by Shu et al. (1987), Bertout (1989) and Appenzeller & Mundt (1989).

It was thus somewhat surprising that X-ray telescopes on the *Einstein*, *ROSAT* and *ASCA* satellites revealed that YSOs are substantial emitters of keV X-rays presumably from plasma at 10^7 K. Enormous numbers of stars at all ages along the Hayashi tracks, plus a few younger protostars, are seen in X-ray images of nearby star forming regions. Except perhaps for the protostars, the emission can be understood as enhanced solar-type magnetic activity where magnetic fields created by plasma motions in the convective interior pop out of the stellar surface. These fields trap and heat plasma to $10^6 - 10^7$ K, particularly during violent magnetic reconnection flares. This solar activity model is supported by a wealth of radio continuum, optical photometric and spectroscopic data. The evidence is clearest for WTT stars, but probably also applies to CTT stars. Reviews of these findings are given in Feigelson et al. (1991), Montmerle et al. (1993) and André (1996), with updates elsewhere in this volume.

YSO X-ray emission may at first appear to have little influence on the astrophysics of star formation and early stellar evolution. While it is considerably greater than solar levels ($L_x/L_{bol} \sim 10^{-5} - 10^{-3}$ compared to 10^{-6} for the Sun today), it is far smaller than, for example, the kinetic energies of outflows believed to significantly affect cloud dynamics. However, we argue here that X-ray astronomy will qualitatively improve our understanding of star formation and pre-main sequence astrophysics in two ways. First, X-ray surveys are (to date) the most effective method for identifying stars older than $\simeq 2$ Myr but not yet arrived on the ZAMS. They can thus provide insights into the star formation history and efficiency of interstellar clouds, and into dynamical processes of star formation (§2 below). Second, X-rays which are absorbed rather than detected will dissociate and ionize. The level of molecular ionization is critical to astrophysical processes of gravitational collapse *via* ambipolar diffusion, magnetocentrifugal acceleration of bipolar outflows by disks, and magnetic disk-star rotational coupling (§3).

Meteorites, especially the pristine carbonaceous chondrites, provide a unique window into the early stages of stellar and disk evolution for our Sun and solar system. Meteoritic properties are extraordinarily varied and are not readily explained by the simple evolutionary sequence outlined above. The flash melting of chondrules, crystalline damage by energetic particles, and complex combinations of isotopic anomalies all require high energy processes within or near the solar system. The magnetic flaring revealed by X-ray observations of YSOs may explain some or all of these phenomena (§4).

2. The census of YSOs

The Chamaeleon I cloud can serve to illustrate the potential for advances in our understanding of star formation issues through X-ray astronomical studies. It is a relatively isolated cloud lying 15° from the Galactic plane at a distance around 140 pc. It has three dense molecular cores within a $500 - 1000$ $M_\odot$ molecular cloud $1° \times 2°$ (2.5×5 pc) in size. Optical, infrared and millimeter surveys locate about 50 T Tauri stars, 20 infrared sources including 3 likely protostars, several molecular outflows and Herbig-Haro objects (Schwartz 1991; Reipurth et al. 1996). Three A0 stars at the tip of the initial mass function (IMF) produce optical reflection nebulae.

A mosaic of soft X-ray images from the *Einstein Observatory* showed 21 X-ray sources associated with stellar objects, of which 5 were previously unknown WTT stars (Feigelson & Kriss 1989). The T Tauri X-ray luminosities appeared to be in the $10^{30} - 10^{31}$ erg/s range, significantly above that seen in ZAMS stars like the Pleiades. But that proved to be an illusion produced by the limited sensitivity and resolution of the *Einstein* study. Images obtained with the improved *ROSAT* observatory with over 80 sources showed that many of the *Einstein* 'sources' were unresolved mixtures of several fainter T Tauri stars (Feigelson et al. 1993). The average T Tauri star now has $L_x \sim 10^{29}$ erg/s. For unclear reasons, the emission is strongly correlated with mass and bolometric luminosity, such that most stars have $L_x/L_{bol} \simeq 1 \times 10^{-4}$. When large T Tauri populations are observed with low X-ray sensitivity, as with the *ROSAT* All-Sky Survey (RASS) or pointed observations of distant star forming regions, only the most luminous stars are detected and the sample L_x/L_{bol} ratio approaches 1×10^{-3}. Except for some of the widely dispersed RASS sources, optical spectroscopy and photometry of previously uncatalogued X-ray stars showed that most are new WTTs.

The result is an enlarged catalog of 117 optically-visible cloud members of which 80 are sufficiently well-characterized to place on the Hertzsprung-Russell diagram for comparison with theoretical models of Hayashi track evolution (Lawson et al. 1996). Though the sample is still deficient in a number of respects (e.g. it is incomplete at masses below $\simeq 0.3$ $M_\odot$ and distances > 1 pc from the cloud cores), it represents one of the best available samples of YSOs associated with an active star forming region. A number of conclusions relevant to star formation astrophysics can be inferred (Feigelson et al. 1993; Lawson et al. 1996; Feigelson 1996):

1. The YSO population is larger than previously thought at all ages along the Hayashi track. The star formation efficiency of the cloud is clearly larger than the few percent inferred from classical T Tauri studies along (Cohen & Kuhi 1979) and may exceed 20%. As X-ray surveys of nearby star forming regions typically increase previously known T Tauri populations by a factor of ~ 2, we infer that the star formation rate of the Galaxy is ~ 2 times higher than previously thought.
2. The presence of a considerable number of WTT stars near the stellar 'birthline' implies that perhaps half of low-mass stars are formed without circumstellar disks or lose their disks within 1 Myr. Since few CTT stars are found at ages > 10 Myr, we conclude that disk longevities can range from $10^5 - 10^7$ yr. This result fully agrees with an independent measure of disk longevities: the distribution of stellar rotational periods which is thought to be regulated by the duration of magnetically mediated star-disk coupling during the CTT phase (Bouvier 1994 and this volume). This result affects the debate over whether the planets in our solar nebula condensed rapidly ($10^4 - 10^5$ yr) or slowly ($\geq 10^6$ yr). The YSO findings permit either slow or fast planet formation.
3. X-ray surveys reveal a few low mass (< 0.5 $M_\odot$) T Tauri stars which were missing in earlier optical surveys. The resulting IMF is inconsistent with an extension of the Salpeter power law IMF but consistent with the Miller-Scalo IMF (Strom & Strom 1994). A similar result has emerged from K-band array surveys of rich PMS clusters, but this technique is ineffective for the more widely distributed stellar populations as in Chamaeleon or Taurus-Auriga.
4. While the IMF is measured by counting stars along Hayashi track isochrones, the star formation history of a cloud is measured perpendicular to isochrones. All existing T Tauri samples show a steep decline in star formation for stars older than $\simeq 2$ Myr. The most convincing explanation is that older stars have drifted away from the active cores, providing that they are not gravitationally bound by the gas. A model based on this concept indicates that the Chamaeleon I cloud has been actively forming stars for about 20 Myr.
5. The RASS has revealed a large population of widely dispersed X-ray bright young stars. While the nature of these stars is still controversial, they appear to be a mixture of ZAMS (perhaps $50 - 100$ Myr old), 'post-T Tauri' stars ($20 - 50$ Myr), and younger WTT stars (Neuhäuser and other contributors in this volume). If some of these are ≤ 10 Myr old, then rapid ejection from star forming regions is needed.

This could be either gravitational slingshot, as when a T Tauri star encounters a hard binary, or stellar velocities inherited from supersonic turbulent motions of the parent molecular cloud. Although no conclusion is yet clear, the kinematics of X-ray discovered stars should eventually provide insights into the dynamical processes underlying low-mass star formation.

3. X-ray effects on cloud and disk

Although X-ray emission is only $10^{-4} - 10^{-3}$ of the bolometric emission of low mass YSOs (and constitutes an even smaller fraction for high mass young stars), it may play crucial astrophysical roles. The keV-energy of an X-ray is sufficient not only to dissociate and ionize a molecule, but to eject an electron with sufficient kinetic energy to produce secondary ionization in surrounding molecules. Previously rare ionized chemical species should be more abundant around X-ray sources, and may trigger unusual sequences of astrochemical reactions (Krolik & Kallman 1983; Yan & Dalgarno 1997). Small-scale molecular gradients are known in molecular cloud cores (van Dishoeck et al. 1993), but the relationship between abundances and X-ray induced chemistry has not been studied. X-ray irradiated dust grains should have modified infrared spectra; for example, emission features from polycyclic aromatic hydrocarbons may be missing (Voit 1991). Such processes might be in part responsible for small-scale variations in infrared dust properties found in active molecular clouds (Abergel et al. 1996). No clear empirical tests of these possible effects of YSO X-rays on molecular and dust properties have been made.

But the most important effect of YSO X-rays on ambient material could be the increased coupling between magnetic fields and molecular gas due to X-ray photoionization. Each YSO in a molecular environment produces an X-ray dissociation region (XDR) where ionization is balanced by recombination, which in turn is affected by the heating of X-ray-produced secondary particles (Maloney et al. 1996). The ionization fraction at a given location thus depends on the gas density and temperature and the column density to each X-ray source. These quantities exhibit considerable variations as one proceeds from the immediate (A.U.) to distant (parsec) scales from a YSO, and change as the YSO evolves from protostellar through T Tauri phases. In addition, a small portion of the energy absorbed by X-radiated dust grains will emerge as photoelectrons (Dwek & Smith 1996). The role of XDRs is thus difficult to quantify; it may prove to be unimportant on some scales and during some evolutionary phases, while it may be critical for astrophysical processes in other circumstances. We outline some possibilities here:

Star formation in molecular clouds It is widely believed that magnetic field pressure impede gravitational collapse in molecular cloud regions that otherwise satisfy the Jeans criterion, resulting in a relatively low star formation rate in many clouds. Under these conditions, gravitational collapse proceeds only through the relatively slow process of ambipolar diffusion (e.g. Mouscovias 1976). Detailed studies of star formation regulation in giant molecular clouds by external sources of ionization, Galactic ultraviolet from OB stars and cosmic ray protons have been made (McKee 1989; Bertholdi & McKee 1995). YSO XDRs represent another element in the equation of photoionization self-regulated star formation (Silk & Norman 1983). Preliminary calculations suggest that X-ray ionization from T Tauri stars with $10^{29} < L_x < 10^{31}$ erg/s in a molecular environment with density $n \simeq 10^5$ cm^{-3} dominates UV and cosmic ray ionization out to $10^3 - 10^4$ A.U. (Carkner & Feigelson, in preparation). This XDR is probably too small to regulate star formation over an entire cloud core, even when a cluster of T Tauri stars are present. The effect should be more important when more massive Herbig Ae/Be, OB and Wolf-Rayet stars with $10^{31} < L_x < 10^{34}$ erg/s are present.

Individual star formation If X-rays turn on sufficiently early during the star formation process, then the XDR may slow ambipolar diffusion and inhibit gravitational infall of envelope material. Conceivably, X-rays may thus be responsible for the transition from Class 0 to Class I protostellar phases, and thus partly determine the mass of the star and the stellar IMF (Silk 1995). X-ray production in Class 0 objects has not be observed (and may never be detected due to the enormous column densities), but might arise from the reconnection of magnetic fields compressed during infall. Norman & Heyvaerts (1985) estimate that $\sim 10^{33}$ erg/s is produced by anomalous Joule dissipation of electric currents generated by MHD microturbulence during cloud collapse. While most of this energy will go into gas heating, a small fraction may emerge in X-rays through magnetic plasma confinement.

Circumstellar disk The influence of YSO X-ray photoionization of disks may provide an important explanation for the complex phenomena of protostars. X-rays in the keV band will penetrate only the outer $\sim 10^{22}$ cm^{-2} of the disk, while ionizing cosmic rays will penetrate $\sim 10^{25}$ cm^{-2}. But the X-ray flux onto the disk may exceed the cosmic ray flux by orders of magnitude, if the geometry is favorable. One likely effect is the promotion of accretion from the disk onto the star (Glassgold et al. 1997). The neutral layer in the plane of the disk may have very low viscosity, while a partially ionized outer layer coupled to an entrained magnetic field will be subject to the Balbus-Hawley instability which causes radial flows and high viscosity. The widely-discussed rotational coupling between disk and star at the corotation radius (e.g. Shu et al. 1994) may be a more complex feedback loop: weak coupling would lead to faster stellar rotation, more magnetic field generation and reconnection, increase X-rays, higher disk ionization, increased accretion into the corotation radius, and thereby stronger disk-star coupling. There is no indication to date that FU Orionis outbursts, likely due to bursts of accretion, are caused or accompanied by higher X-ray emission.

A second implication of X-ray photoionization of disk outer layers concerns the coupling of disk motions to bipolar outflows and winds. Outflows may emerge from the outer regions of the cold disk (e.g. Pudritz & Norman 1983), from the inner regions where stellar fields encounter the disk (Najita & Shu 1994; Hayashi et al. 1996), or both regions. In any case, ionization is needed to link circular motions in the disk to outward motions of the flow. While this ionization has been attributed to cosmic rays, YSO X-rays may be the dominant source.

4. Flares and the solar nebula

4.1. Meteoritic evidence

The meteoritic record provides a tangled and incomplete fossil record of conditions in the solar nebula (Kerridge & Matthews 1989). Meteorites exhibit an astonishing variety of petrographic, crystalline, elemental and isotopic properties. While some properties are largely understood (e.g. shocked rock from collisions; melted metals from differentiated planetesimal interiors; recent impact ejecta from the Moon or Mars), others are enigmatic. The carbonaceous chondrite class of meteorites are the most pristine. Dated to 4.55 Gyr from radioactive isotopes, they contain 'pre-solar grains' (i.e. interstellar dust particles) of silicon carbide, diamond and graphitic carbon which, by virtue of unusual isotopic compositions, can be individually associated with ejecta from AGB winds, novae and supernova. But most of their mass consists of chondrites embedded in a hydrocarbon matrix similar to coal, both of which are poorly understood.

Most meteorites are chondrites, comprised largely of melted silicate globules millimeters in size. Laboratory experiments indicate that they were flash heated to $1500-2000$ C and then slowly cooled. The physical cause of chondrule melting has been widely discussed for over a century without resolution. Chondrules are often covered with 'rims' of rocky particles with different composition than the chondrules themselves. These are probably accreted from the nebula during the period between chondrule melting and incorporation into the larger meteoritic body. Some chondrules in carbonaceous chondrites have unusual elemental and isotopic compositions. In particular, Ca-Al-rich inclusions (CAIs) can have very puzzling fractionated and unidentified nuclear (FUN) anomalies. Isotopic anomalies are present for many elements: H, O, Al, Ca, Mn, Fe, Xe, Ag, La, Pd, Sm, I, and others. The presence of short-lived nuclides like ^{41}Ca and ^{26}Al ($t_{1/2} = 0.15$ Myr and 1.1 Myr respectively) indicate that portions of the solar nebula must have produced or been contaminated with freshly synthesized nuclear products immediately prior to the formation of some inclusions and chondrules.

For some grains in carbonaceous chondrites, the exposure to energetic particles can be measured in two ways. A few percent of these grains show considerable excesses of spallogenic ^{21}Ne and similarly high densities of particle tracks from heavy nuclei. Surrounding grains do not show these effects, indicating they arose when the grains were freely floating in the solar nebula prior to incorporation into the meteorite. The only reasonable explanation for this unusual particle irradiation history is exposure to solar flare particles at levels far above that produced by the contemporary Sun. This is perhaps the clearest case where meteorites show direct effects of the flaring activity seen by X-ray telescopes (Woolum & Hohenberg 1993).

Finally, we note that polarization analysis of chondrule material indicates that their condensation occurred in the presence of a $\sim 1-10$ G magnetic field. This 'natural remnant magnetization' indicates that the solar nebula contained substantial fields, either inherited from the parent molecular cloud or generated *in situ* (Saguira & Strangway 1988).

4.2. Links to YSO flares

It has proved to be extremely difficult to accommodate the varied, sometimes bizarre, properties of meteorites with the simple star-plus-disk formation scenario outlined in §1. Chondrule melting has been ascribed to a dozen physical causes – shocks from inhomogeneous accretion onto the nebula, shock within the nebula, ablation in protoplanetary atmospheres, impacts onto parent bodies, FU Orionis outbursts, nebular lightning, and magnetic reconnection flares – but no model has gained ascendancy (Wasson 1993; Hewins et al. 1996). External contamination models for isotopic anomalies encounter difficulties. For example, a Type II supernova sufficiently close to produce the ^{41}Ca does not make sufficient ^{26}Al and its shock will disrupt the molecular cloud. An AGB star during dredge-up phase passing through the molecular cloud could account for the ^{26}Al but not the observed ^{53}Mn.

Isotopic anomaly models based on spallation by energetic protons, either from an external supernova or flares within the solar system, may be more successful. These models have been considered for decades (e.g. Fowler et al. 1962; Clayton et al. 1977; Feigelson 1982; Levy & Araki 1989), but have not been particularly favored over alternatives until very recently. The meteoritic community has not fully recognized that the presence of powerful magnetic flares in the early Sun-nebula system is not an unfounded hypothesis, but rather is strongly indicated by a large body of X-ray and radio astronomical studies of YSOs. We outline here two recent models by leading meteoritic scholars that illustrate the role that YSO flares may play in the formation of the Sun and planetary system.

Cameron (1995) envisions the process in four steps. In Stage 1, the molecular cloud core undergoes collapse in < 1 Myr, already contaminated by ^{41}Ca from a nearby AGB star or supernova (via cosmic ray spallation). Stage 2 is a brief phase of FU Orionis accretion bursts and outflows, lasting perhaps 0.05 Myr, during which the Sun acquires most of its mass and CAIs form with uniform abundances of ^{26}Al and other short-lived nuclides. Stage 3 is the CTT phase of $1-2$ Myr, during which carbonaceous chondrites form and the Jovian planets grow. Stage 4 is the lengthy WTT phase when the nebula decouples from the Sun. Most chondrules form during this late phase with no short-lived nuclides, melted by magnetic reconnection flares at the bow shock between the solar wind and disk. These can be associated with the X-ray flares seen in WTTs.

A second view is developed by Shu et al. (1997) and Lee et al. (1997) based on the X-wind model of CTT stars. Here, the stellar magnetic field penetrates the nebula at the Alfvèn radius around 5 $R_\star$ where angular momentum coupling between the star and disk results in the ejection of some material in a wind and the funneling of other material along field lines onto the star. Coagulated balls of dust particles are lifted by the outflow where they are flash melted into chondrules by flares either near the stellar surface or arising from reconnection of field lines above the Alfvén radius. During this process, the chondrules are subjected to MeV particle irradiation producing isotopic anomalies. For instance, the troublesome ^{41}Ca anomaly can arise from ^{42}Ca(p,pn)^{41}Ca and ^{40}Ca(α,^{3}He)^{41}Ca. The high abundances of ^{26}Al in some chondrules is attributed to irradiation by ^{3}He-rich events analogous to solar impulsive flares, as with ^{24}Mg(^{3}He,p)^{26}Al. Overproduction of ^{41}Ca is avoided by particle absorption in thick rims. In Shu & Lee's view, CAIs and chondrules are coeval but are formed in different locations. The CAIs are from flare-melted inflowing material which fall out from the funnel flow into the disk.

These explanations of the complex properties of ancient meteorites, while different in important respects, are both linked to the X-ray and radio continuum flares in YSOs. Cameron's model links chondrule formation to flares seen in WTT stars all along the Hayashi tracks. Shu & Lee's model associates CAI and chondrule formation with flares during the earlier protostellar and CTT phases. Circularly polarized radio flares (see André 1996) directly trace particle acceleration to MeV energies required for spallogenic nuclear reactions and, providing solar reconnection events are a useful guide, the X-ray flares will be accompanied by strong propagating shocks that would melt dustballs into chondrules.

5. Future work

There is little doubt concerning the empirical evidence for high levels of X-ray emission and flaring activity in YSOs. The X-ray imaging data, supported by radio continuum and optical observations, are extensive and convincing. However, there is increasing uncertainty as one recedes from the data into interpretation and implications. For example, the geometry of the magnetic field undergoing reconnection flares is not definitely known. The WTT and CTT data are consistent with multipolar fields connected to the stellar surface, as in the Sun (Feigelson et al. 1991). But flares could be produced above the disk where stellar and disk fields are linked (Hayashi et al. 1996; Shu et al. 1997). Interpreters of the meteoritic evidence for high-energy processes, such as chondrule melting and isotopic anomalies, prefer that the flares be located directly over the disk to ensure proximity to the flare shocks and spallating particles (Levy & Araki 1979; Cameron 1995; Lee et al. 1997). Magnetic fields on A.U.-scales may be necessary to explain an extremely powerful flare recently seen in a protostar (Grosso et al. 1997).

YSO observations acquired to date also cannot clearly determine when specific solar nebular processes occurred. Chondrules may be melted in the protostellar, CTT or WTT phases, and the longevity of the Sun's disk could be anything from 10^5 to 10^7 years. Progress on these issues require innovative YSO observations that are attuned to the theoretical issues raised by interpreters of meteorites and the solar nebula.

On larger scales, the influence of YSO X-rays on the environment can probably be subject to straightforward tests. Millimeter interferometers can search for ionized molecular species or other unusual chemistry in the vicinity of embedded X-ray luminous YSOs. The *Infrared Space Observatory* may detect alterations in dust properties caused by X-ray processing. Unbiased optical spectroscopic surveys can confirm star formation histories and stellar kinematic measurements can test theories of YSO dispersal raised by X-ray studies.

Altogether, though little relationship between high-energy astronomy and star formation was expected, X-ray astronomy is primed to provide significant new insights into the astrophysics of star formation and the solar nebula. Considerable theoretical research is needed to establish which of the many possible effects are truly important.

Acknowledgements

This work was supported by NASA grants NAGW-2120, NAG5-3404 and NAS8-38252.

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