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X-RAYS FROM THE YOUNGEST STARS

Eric D. FEIGELSON
Department of Astronomy & Astrophysics, Pennsylvania State University, University Park PA 16802 USA

Abstract:

The X-ray properties of classical and weak-lined T Tauri stars are briefly reviewed, emphasizing recent results from the *ROSAT* satellite and prospects for *ASCA*. The interpretation of the high level of T Tauri X-rays as enhanced solar-type magnetic activity is discussed and criticized. The census of X-ray emitters is significantly increasing estimates of galactic star formation efficiency, and X-ray emission may be important for self-regulation of star formation. *ASCA* images will detect star formation regions out to several kiloparsecs and will study the magnetically heated plasma around T Tauri stars. However, images will often suffer from crowding effects.

1. Introduction

In a series of seminal studies, Hayashi (1966) calculated that a solar-mass young star descends almost vertically down the Hertzsprung-Russell diagram with a fully convective interior, whence it moves to the left to reach the zero-age main sequence. Recent numerical models confirm this basic result. This evolution, however, does not treat the circumstellar matter, which can affect or even dominate the radiative emission of the young stellar object. Insight into the star's environment as it descends its Hayashi track has emerged principally from infrared, millimeter and radio studies. Shu *et al.* (1987) incorporate the optical and infrared results into a four-stage scenario for star formation: (a) the molecular cloud cores, commencing gravitational collapse mediated through ambipolar diffusion; (b) protostars with gas infalling onto a circumstellar disk; (c) protostars where a bipolar outflow coexists with the inflow; and (d) classical T Tauri stars, where infall has terminated, revealing an optically visible stars interacting with its accretion disk. To this, one can add a fifth stage: (e) a post T Tauri star that has lost its disk, as the star moves toward the zero-age main sequence. These stages have characteristic intensities and spectra in the mid-infrared bands: stages (b) through (e) correspond to Class 0 through 3 infrared sources (André & Montmerle 1994).

All of the processes outlined above involve relative cool thermal gases with temperatures ranging from 10 K for the molecular clouds to 3000 K for the T Tauri photospheres. Main sequence stars do emit X-rays from magnetically confined hot plasma in coronae and flares. But main sequence stars at the distance of star forming regions would produce only $< 10^{-15}$

erg/s/cm^2 flux in the soft X-ray band. It was thus a considerable surprise that early *Einstein Observatory* X-ray images of nearby star forming clouds revealed dozens of compact sources associated with low mass pre-main sequence stars with fluxes around 10^{-13} erg/s/cm^2. *ROSAT* observations with more sensitivity and higher spatial resolution are finding hundreds of new of X-ray emitting T Tauri stars. Furthermore, *Tenma* and *Ginga* satellite observations of these regions, while unable to resolve them into individual sources, establishes that the hard X-ray emission is yet another component of T Tauri emission, in some cases order of magnitude stronger than that seen in the soft X-ray band.

Extensive research has been conducted to investigate this excess X-ray emission from T Tauri stars, reviewed in detail with many references by Bertout (1989), Feigelson *et al.* (1991) and Montmerle *et al.* (1993). We can mention only a few results here, concentrating on the most recent findings.

2. X-ray Properties of T Tauri Stars

X-ray studies of pre-main sequence stars have concentrated on the nearest star forming clouds about 150 pc away, lying just outside the local 'hot bubble' surrounding the Sun. These regions include the Taurus-Auriga complex covering several hundred square degrees in the northern sky, and smaller clouds in the southern sky such as the Ophiuchi, Corona Australis, Chamaeleon and Lupi clouds (see map in Dame *et al.* 1987). The Orion molecular cloud, about 450 pc distant, is also extremely rich in X-ray sources, but the X-ray fluxes are reduced and crowding is worse.

A soft X-ray image of these nearby star forming regions typically shows dozens of faint X-ray sources associated with stars in and around the molecular cores. Many of these are previously studied 'classical' T Tauri (CTT) stars, with strong broad optical emission lines attributed to an outflowing wind or accreting gas and strong infrared excesses produced by a cool dusty circumstellar disk. However, the majority of X-ray selected stars are 'weak-lined' T Tauri stars (WTT) which exhibit only a weak variable Hα line and little or no infrared excess. Initially these were thought to be the missing post-T Tauri stars (stage e above), but many of the X-ray WTT stars are as luminous (hence as young) as CTT stars. CTT and WTT stars have similar X-ray luminosity functions, ranging from several $\times 10^{30}$ to a sensitivity limit of several $\times 10^{28}$ erg/s in the soft X-ray band.

Repeated observations show that virtually all CTT and WTT are variable in X-rays on timescales of days. Perhaps one percent of these stars are undergoing a powerful flare up to 10^{31} erg/s on timescales of minutes or hours during any single observation. The X-ray spectra of most T Tauri tars can be modeled in terms of a soft (0.4 keV) and a harder (1.5 keV) component, with different amounts of foreground absorption depending on the star's position in the molecular cloud. However, *Tenma* and *Ginga* non-imaging observations of the ρ Ophiuchi cloud show that some T Tauri stars emit very strongly in the 2-10 keV band with an iron line at 6.7 keV (Koyama 1992). Variability in this hard band suggests that only one or a few stars are responsible for this component, although its power may exceed that from all of the soft X-ray emitters combined.

Observations now emerging from *ROSAT* pointed observations with the Position Sensitive Proportional Counter are quite spectacular. A mosaic 6 ksec exposures of the Chamaeleon I cloud shows 89 sources, of which 20-35 are previously unreported WTT stars (Feigelson *et al.* 1993). A much longer exposure sees few additional sources, suggesting that the bulk of the T Tauri population is now seen (Krautter *et al.* 1994). A very deep image of the L1495E cloud in Taurus-Auriga reveals a new group of low mass T Tauri M stars, giving an initial mass function compatible with that seen in the solar neighborhood (Strom & Strom 1994). The *ROSAT*-discovered stars may soon outnumber all previously known T Tauri stars. A mosaic of 17 pointings towards the Orion molecular cloud has over 600 X-ray sources (Walter 1994), and preliminary results from optical followup of the *ROSAT* all-sky survey indicate that as many as 450-500 new WTTs may be found in the Taurus-Auriga clouds (Neuhauser *et al.* 1994). In addition to surveys for new WTT stars, important individual stars have been studied in detail. A simultaneous *ROSAT*/radio/optical campaign of the luminous WTT star HD 283447 showed strong but constant X-ray and chromospheric activity simultaneous with rapidly variable radio emission (Feigelson *et al.* 1994).

3. The Solar Activity Interpretation

These X-ray properties bear a significant resemblance to those seen in magnetically active late-type stars such as dMe flare stars, tidally spun-up RS CVn binary systems, and the Sun. In each case, plasma is heated to X-ray temperatures by continuous and/or explosive processes, and is trapped in in a complex multipolar configurations of closed magnetic structures attached to the stellar surface. If the X-ray emission of T Tauri stars arises from solar-type magnetic activity, then the total plasma emission must be 2-4 orders of magnitude greater than in the Sun. Simple cooling loop models of X-ray flares in T Tauri stars, with peak luminosities around L_x(0.5-4.5 keV) $\sim 10^{31}$ erg/s and decay times of hours, suggest that the plasma densities are similar to solar values but the loop sizes are much larger around 10^{11} cm. Similar X-ray flares and emission measures are seen from RS CVn systems.

Considerable evidence from other spectral bands has emerged supporting the enhanced solar activity model of T Tauri X-ray emission (see Feigelson *et al.* 1991 for a detailed review). Optical photometric monitoring of X-ray luminous WTT stars often show rotational modulation of cool spots covering 5-40% of the stellar surface. In one WTT star, rapid photometry caught a white light continuum flare causing $\Delta U = 0.4$ magnitudes in 20 minutes. In many cases, optical and ultraviolet spectroscopy reveals greatly enhanced chromospheric emission lines. This has been known for several decades and led to the 'deep chromosphere' model for WTT stars.

Radio continuum flares with power up to 10^{18} erg/s/Hz, or 10^5 times peak solar levels, are seen in some WTT stars. The radio spectra are flat or inverted, and circular polarization is seen in a few cases which demonstrates that solar-type gyrosynchrotron emission is present. Very Long Baseline Interferometry has resolved these radio emitting regions in the brightest stars, showing variable sizes from less than a stellar radius to 5-20 $R_\star$ (Phillips *et al.* 1991). (Recall that along the Hayashi track stars typically have radii $R_\star \simeq 2 - 3R_\odot$.) This observationally supports earlier inferences from the X-ray flares that the magnetic structures in WTT stars are orders of magnitude larger than in the Sun.

All of these properties can be qualitatively understood within the context of magnetic dynamo theory. T Tauri stars are rapidly rotating due to angular momentum inherited from the molecular cloud, and their interiors are fully convective. Any small magnetic fields in the interior should be rapidly amplified via the $\alpha - \omega$ dynamo mechanism, and would emerge on the surface causing plage, starspots, chromospheric emission and coronal heating. Sudden reconnection of the fields would lead to the powerful flares detected on WTT stars. The large population of observed X-ray WTT stars indicates that passage through this magnetically active phase is common to most or all low mass stars. We conclude from this model that solar-type stars exhibit their highest levels of magnetic activity during their T Tauri phase (Feigelson *et al.* 1991).

4. Open Issues

Despite the attractiveness of this solar analogy, a number of difficulties are apparent. First, the correlation between L_x and surface rotation, expected from the magnetic dynamo model and seen in late-type main sequence stars, is weak or absent in WTT stars. Second, an unpredicted strong relationship between L_x and the total luminosity of the star $L_\star$ is seen. Most of the X-ray emission can be readily accounted for by the simple expression

$L_x/L_\star = 1.6 \times 10^{-4}$ (Feigelson *et al.* 1993). $L_\star$ is jointly correlated with stellar mass, radius and age, so the link with L_x is not clearly identified. Third, it is implausible that a magnetic loop or arcade can persist when it is attached to a rapidly rotating star and extends several times the stellar radius. Centrifugal forces and magnetic hydrodynamic instabilities should disrupt the fields; yet WTT radio structures have been observed to persist for years. Fourth, the extraordinarily luminous 2-6 keV component seen with the *Tenma* and *Ginga* satellites requires flare processes in excess of those seen in magnetically active late-type stars. It is unclear whether many or only one T Tauri star is responsible for this hard component.

The first two problems may indicate that the dynamo is not the principal source of magnetic fields in pre-main sequence stars. It is conceivable that 'fossil' fields inherited from the star formation process dominate (Tayler 1987), and indicators of surface magnetic activity will correlate with global properties like luminosity and mass rather than with surface rotation rate. The third problem may indicate that the magnetic field geometry may not be multipolar as on the Sun. Alternative field geometries include: a global dipole; fields connecting the star and a circumstellar disk at the corotation radius; fields within a cicumstellar disk; and field lines connecting two close binary stellar companions (see Montmerle *et al.* 1993; Feigelson *et al.* 1994). The possibility that T Tauri radio or X-ray emission arises in fields linking the stellar surface and circumstellar disk is quite attractive, as evidence concerning T Tauri surface rotation (Edwards *et al.* 1993) and models of the emission line winds (Shu *et al.* 1994) independently suggest that magnetic star-disk coupling is present.

5. Broader Implications of T Tauri X-ray Emission

The cold molecular environment where star formation occurs may be strongly affected by the presence of X-ray emitting T Tauri stars. In the ρ Ophiuchi cloud cores, the density of ionizing X-radiation exceedsd that of galactic cosmic rays, particularly in the immediate vicinity of T Tauri stars (Casanova *et al.* 1994). Pockets of higher fractional ionization should result, slowing ambipolar diffusion and inhibiting gravitational collapse and further star formation. Thus, T Tauri X-rays may be an important mechanism for the self-regulation of star formation in the galaxy (Silk & Norman 1983). Flares from the young star may also affect the circumstellar disk. There is considerable evidence for enhanced flaring in the early Sun from analysis of ancient gas-rich meteorites (Caffee *et al.* 1991).

Imaging X-ray studies are also significantly revising our knowledge of the star formation process in the galaxy in several ways. First, the discovery of many WTT stars far up the Hayashi track, coeval with the younger CTT stars, indicates that star formation scenario outlined in the Introduction may be too simple. Either some stars are born without any circumstellar disks, or more likely, the loss of disks can occur at very early times ($< 10^6$ yr). Second, the existence of young WTT stars also implies that the star formation efficiency of molecular clouds is considerably higher than previously thought. *ROSAT* data suggests that the number of WTT stars exceeds the CTT stars by 2-3:1 and conceivably even higher (Neuhäuser *et al.* 1994). Thus, X-ray astronomy unexpectedly provides new insight into the star formation rate of the Galaxy.

6. Prospects for *ASCA*

ASCA has high sensitivity in both the soft X-ray band seen with in *Einstein* and *ROSAT* images, and in the hard X-ray band detected but not imaged with *Tenma* and *Ginga*. *ASCA* will show complex multisource images in all nearby star forming regions, and will detect similar regions out to $\simeq$2 kpc in modest exposure times. *ASCA* can thus map star formation in the nearby disk of our Galaxy, including the large WTT population that is missed in many infrared surveys. The presence of intevening clouds or spiral arms will not impede these detections. *ASCA* will determine which star(s) are responsible for the strong 2-10 keV component and the iron line emission. Its unique ability to image at harder energies permits *ASCA* to peer directly through cloud cores up to $A_V \simeq 100$, seeing all CTT and WTT stars independent of their location in the cloud. It will be particularly interesting to see whether *ASCA* images confirm the suggestion from *ROSAT* that stars emit X-rays even in their protostellar phase (Casanova *et al.* 1994). Finally, *ASCA*'s spectroscopic capabilities will define the nature of the multitemperature plasma around T Tauri stars. The spectral evolution of a flare, if one happens to occur during an *ASCA* exposure, will be particularly important and may elucidate uncertainties about the magnetic field geometry.

The principal difficulty *ASCA* studies will encounter is crowding. The surface density of T Tauri stars through a molecular cloud ranges from $\sim$ 100 stars/arcmin^2 in the center of Orion to $\sim$100 stars/deg^2 in the core of Ophiuchus to $\leq$10 stars/deg^2 in the Taurus clouds. In addition, over half of T Tauri stars have recently been shown to lie in binary systems. In the more crowded regions, *ASCA* images will show the few brightest stars plus a blur from the rest. The first *ASCA* images of the central region of the ρ Ophiuchi cloud reported at this conference are of this type (Koyama *et al.* 1994).

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