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HIGH-ENERGY PROCESSES IN YOUNG STELLAR OBJECTS

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■ **Abstract** Observational studies of low-mass stars during their early stages of evolution, from protostars through the zero-age main sequence, show highly elevated levels of magnetic activity. This activity includes strong fields covering much of the stellar surface and powerful magnetic reconnection flares seen in the X-ray and radio bands. The flaring may occur in the stellar magnetosphere, at the star-disk interface, or above the circumstellar disk. Ionization from the resulting high-energy radiation may have important effects on the astrophysics of the disk, such as promotion of accretion and coupling to outflows, and on the surrounding interstellar medium. The bombardment of solids in the solar nebula by flare shocks and energetic particles may account for various properties of meteorites, such as chondrule melting and spallogenic isotopes. X-ray surveys also improve our samples of young stars, particularly in the weak-lined T Tauri phase after disks have dissipated, with implications for our understanding of star formation in the solar neighborhood.

1. INTRODUCTION

The formation and early evolution of low-mass[1] stars is generally discussed in terms of gravitational and hydrodynamical processes. A molecular cloud core collapses, a protostar emerges at the center while high-angular-momentum material forms a circumstellar accretion disk and bipolar outflows are produced. The star becomes visible, contracting quasistatically along the Hayashi and radiative tracks

[1]This review is restricted to solarlike stars with masses around $M_* \sim 0.2 – 2\ M_\odot$ and omits discussion of OB stars and intermediate-mass Herbig Ae/Be stars (Waelkens & Waters 1998). We further apply the expression "young stellar objects" (YSOs) to all phases of low-mass evolution before arrival at the main sequence.

in the T Tauri phase to the zero-age main sequence (ZAMS). Magnetic fields are believed to play a central role in regulating collapse through ambipolar diffusion and in transferring disk orbital motion to collimated outflows. Coupling between the neutral material and magnetic fields is thought to be provided by an approximate 10^{-8} fractional ionization produced by low-energy, galactic cosmic ray interaction with the molecular gas. Ancient meteorites indicate that additional high-energy processes affected the solar nebula, but the origins of these processes cannot be ascertained and are often omitted from astrophysical discussions of star formation and YSOs. (A notable exception is the "Protostars & Planets" series of meetings—Levy & Lunine 1993, Mannings et al 1999.)

However, empirical studies of YSOs in the 1980s and 1990s provide direct and ample evidence for kilo electron volt-energy radiation and MeV particles produced within protostellar and T Tauri systems. The X-ray emission is understood to be thermal emission from gas rapidly heated to temperatures 10^7 K by violent magnetohydrodynamical (MHD) reconnection events, analogous to solar magnetic flaring but elevated by factors of 10^1 to 10^6 above levels seen on the contemporary Sun. Other indicators of strong magnetic activity include large star spots revealed by optical photometry, an enhanced chromosphere and Zeeman effects seen in optical and ultraviolet spectroscopy, and powerful nonthermal radio-continuum flares.

These results reveal a deep relationship between high-energy phenomena observed in YSOs, the Sun, and other magnetically active late-type stars such as dMe flare stars and RS CVn binary systems. For 50 years, the Sun has been known to be an X-ray emitter, and the X-ray emission of the solar surface is now monitored in great spatial and spectral detail. Images from solar X-ray satellites show hot plasma, largely confined within magnetic loops, which can be suddenly heated by magnetic reconnection events (flares), often accompanied by ejection of substantial amounts of matter (coronal mass ejections and solar energetic particles). Circularly polarized gyrosynchrotron emission at radio wavelengths indicates the acceleration of electrons to mildly relativistic energies, and nuclear gamma-ray lines are produced by spallation reactions of energetic protons in the photosphere. All of these phenomena are observed or inferred to be present in YSOs at elevated levels.

These observations raise many astrophysical issues. The magnetic activity in YSOs may arise, as in the Sun, from a magnetic dynamo generated in the deep convection zones of the stellar interior. But the magnetic-field topologies cannot easily be predicted or deduced from activity tracers. The circumstellar material of YSOs may allow unusual magnetic configurations—such as star-disk, star-envelope, or disk-disk fields—that are not seen in older cool stars. Furthermore, magnetic activity may provide a crucial astrophysical link between the central star, circumstellar envelope, disk, and bipolar ejecta in YSOs.

X-ray ionization of circumstellar material will typically dominate galactic cosmic ray ionization on scales to approximately 10^4 AU and thus should be a major player in the dynamics and evolution of protoplanetary disks. The integrated effects of particle irradiation from YSO flaring may account for a variety of characteristics in the meteoritic record of the solar nebula. Finally, YSO magnetic activity also leads to insights regarding the population of young stars. X-ray surveys of large areas in the sky considerably enlarge the census of YSOs, both in star-forming regions and away from them, addressing such diverse problems as the star formation histories of molecular clouds, the longevity of circumstellar disks, and the kinematic dispersal of young stars into the galaxy.

After covering some background material on YSOs (Section 2), this review describes the evidence for YSO magnetic activity revealed in multiwavelength studies (Section 3). Astrophysical models of YSO magnetic fields are outlined in Section 4, followed by discussion of high-energy irradiation of interstellar and circumstellar material (Section 5). Section 6 reviews magnetic activity as a tracer of YSO populations, and Section 7 gives concluding remarks.

2. BACKGROUND

The first concepts of star formation via gravitational collapse were established by Pierre-Simon Laplace, whose *Exposition du Système du Monde* (1796) gives a vivid scenario of the formation of the Sun and the solar system from a rotating nebula. In the first half of this century, Edward Barnard and others speculated that dark clouds were the sites of stellar birth (Trimble 1996). Alfred Joy (1945) reported a class of unusual emission line and variable stars near dark clouds, representing newly formed stars, now called classical T Tauri (CTT) stars, which were found to be frequently grouped in “T associations” (Ambartsumian & Mirzoyan 1982).

During the 1980s and 1990s, a revolution took place in infrared and millimeter astronomy, which led to direct observational searches for the earlier infall and protostellar phases embedded deep in the clouds. Although the simple Laplacian picture lies at the foundation of contemporary models, the detailed astrophysics of YSOs proved to be much more complex than a simple self-gravitating nebula, and our understanding of YSOs has not proceeded in a simple fashion. Much of the thinking can be viewed as the interweaving of five themes.

2.1 Pre-Main Sequence Stellar Evolution

The basic picture established by early analytical treatments of YSO stellar interiors (Hayashi 1966) is still in force. T Tauri stars have fully convective stellar interiors with monotonically decreasing luminosities but nearly constant surface temperatures, powered principally by gravitational contraction rather than nuclear reactions. Models based on different assumptions regarding atomic opacities and convective structure give somewhat different isochrones on the Hertzsprung-Russell diagram. The rotational evolution of stars along the Hayashi tracks may be complex, and the resulting magnetic field generation is not well established. A YSO with a differentially rotating interior could generate a core field as high as approximately 10^6 G in 10^3 years, but turbulence without differential rotation would dissipate the field (Levy et al 1991).

2.2 Outflows

The broad emission lines of CTT stars often exhibit P Cygni-type profiles and were originally interpreted as dense hot winds (Herbig 1962, Kuhi 1964). Collimated outflow bow shocks seen as Herbig-Haro objects, small-scale optical jets, and molecular bipolar outflows were later found to be common among the younger YSOs (see reviews by Bachiller 1996, Reipurth & Bertout 1997). It was readily perceived that the YSO outflows are not accelerated by radiation or coronal gas pressure but that they required the intervention of magnetic fields and the circumstellar disk (e.g. DeCampli 1981, Pudritz & Norman 1983, Uchida & Shibata 1984). Although there is a consensus that magnetic fields confine and accelerate outflows, the detailed acceleration mechanism close to the star is still the subject of lively discussion (Pudritz et al 1999).

2.3 Disks

Although the optical obscuration of most YSOs was originally attributed to a spherical cocoon of unaccreted dusty material, the discovery of intense emission from the micrometer to the millimeter bands from CTT stars over the past 15 years requires that large amounts of dust be present in a flattened disk. These protoplanetary disks can now be directly imaged in emission with millimeter interferometers (e.g. Dutrey et al 1994), and the Hubble Space Telescope in visible light silhouette (McCaughrean & O'Dell 1996) or in near-infrared emission (Stapelfeldt et al 1998).

2.4 Accretion

Whereas star formation theory predicts stellar growth by accretion from a large circumstellar envelope (Shu et al 1987), direct evidence for infall proved elusive for many years. Doppler signatures of gas infall are now seen in the earliest protostellar phases (e.g. Zhou et al 1993, Mardones et al 1997). Ballistic infall models, including rotation, indicate that the envelope feeds a central accretion disk several hundred astronomical units in size (Terebey et al 1984), consistent with recent disk imaging. Some molecular line evidence of disk accretion has also been found (Ohashi et al 1996). After the envelope is cleared by outflows, this disk remains, and the material accretes onto the central star on time scales of 10^5–10^6 years. This process can proceed in a relatively steady fashion—seen as CTT stars—or in short-lived episodes of high accretion with associated ejection of material—seen in YY Ori stars (Bertout et al 1996) and at very high levels as FU Orionis stars (Hartmann et al 1993). Detailed models of T Tauri-permitted line profiles and continuum veiling—historically attributed to outflows or star-disk boundary layers—are now explained as emission in magnetically confined accretion columns

(Hartmann et al 1994, Hartmann 1998, Calvet & Gullbring 1998). Accretion also affects pre-main sequence evolutionary tracks (Siess et al 1997).

2.5 Magnetic Activity

Several independent lines of evidence indicated that YSOs exhibit unusually high levels of magnetic activity. The original perception by Joy (1945) that YSO spectra share characteristics with the solar chromosphere led to the development of T Tauri stellar atmospheres with large plage regions and deep chromospheres (Herbig & Soderblom 1980, Calvet et al 1984, Finkenzeller & Basri 1987). Hundreds of flash variable stars in star-forming regions were found, which suggests an analogy with dMe flare stars (Haro & Chavira 1966, Ambartsumian & Mirzoyan 1982). Powerful X-ray flares from T Tauri stars were found with the first satellite-borne imaging X-ray telescope, and these flares were generally interpreted as enhanced solar-type emission (Feigelson & DeCampli 1981, Walter & Kuhi 1981, Montmerle et al 1983, Feigelson et al 1991). Gyrosynchrotron radio-continuum flares, similar in character but again orders-of-magnitude stronger than solar levels, were found in some YSOs (Feigelson & Montmerle 1985, White et al 1992b).

2.6 Stages of YSD Evolution

Although this review concentrates on the theme of magnetic activity, we trace recent efforts to synthesize all previous approaches into a coherent understanding of YSO astrophysics. For example, we discuss the possible origin of flares in magnetic field lines connecting the star to the disk and the possible roles of energetic radiation for ionizing the disk and promoting accretion and outflow. We summarize here some central concepts that underlie our discussion of magnetic and high-energy processes, recognizing that our treatment does not adequately present the rich phenomenology and astrophysics of YSOs (cf. Levy & Lunine 1993, Mannings et al 1999).

Figure 1 illustrates the principal phases of YSO evolution: protostars, CTT stars, and weak-lined T Tauri (WTT) stars. To reduce the effects of foreground extinction (T Tauri stars are often optically visible, whereas protostars are deeply embedded in their parent cloud), the evolutionary phase of YSOs is generally classified by their infrared-millimeter spectral energy distributions (Lada 1987, André & Montmerle 1994).

Class 0 infrared-millimeter sources are young protostars with massive, cold ($\sim$30 K) envelopes that collapse toward the central regions. A collimated outflow and a disk rapidly form within the envelope, which is 10^3 to 10^4 AU in size (Figure 2 *left*). The age of Class 0 sources is approximately 10^4 years.

Class I sources have ages of approximately 10^5 years. Most of the material in the envelope has accreted onto the disk or star, and the disk is a few hundred astronomical units in extent (Figure 2 *middle*). Outflow activity is still present but with a larger opening angle and a lower mass-loss rate than at the Class 0 stage (Bontemps et al 1996).

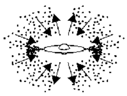
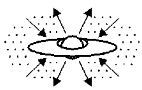
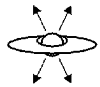
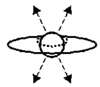
Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
Age (years)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/Infrared Class	Class 0	Class I	Class II	Class III	(Class III)
Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

Figure 1 The stages of low-mass young stellar evolution. This review chiefly addresses the bottom three rows of the chart. (Adapted from Carkner 1998.)

Class II is the infrared designation of CTT stars. Most of their complex phenomenology can be modeled as a star interacting with a circumstellar accretion disk (Figure 2 *right*). The youngest members of the class drive outflows, and all drive strong winds with $\dot{M} \approx 10^{-7}\ M_{\odot}\ \mathrm{year}^{-1}$ and $v_w \sim 200\ \mathrm{km\ s}^{-1}$. Contemporary models are based on magnetically confined accretion from a magnetosphere extending out to the corotation radius (Figure 3). When Class II sources are unobscured, they can be placed on the Hertzsprung-Russell diagram and compared with theoretical evolutionary tracks. The derived ages are mostly between 0.5 and 3 million years (Myr), although some stars retain CTT characteristics as long as approximately 20 Myr.

Class III infrared sources, or WTT stars, have simple blackbody spectral-energy distributions, which implies little or no accretion disk (Wolk & Walter 1996). Many WTT stars occupy the same region on the Hertzsprung-Russell diagram as do CTT stars, although some are approaching the ZAMS. It is tantalizing to surmise that the loss of disks from the Class II–III phases is accompanied by planet formation, because roughly one-third of CTT stars have disks sufficiently massive to produce the primitive solar nebula (e.g. Beckwith et al 1990, André & Montmerle 1994). For stellar ages more than 20 to 30 Myr, all indications of circumstellar disks

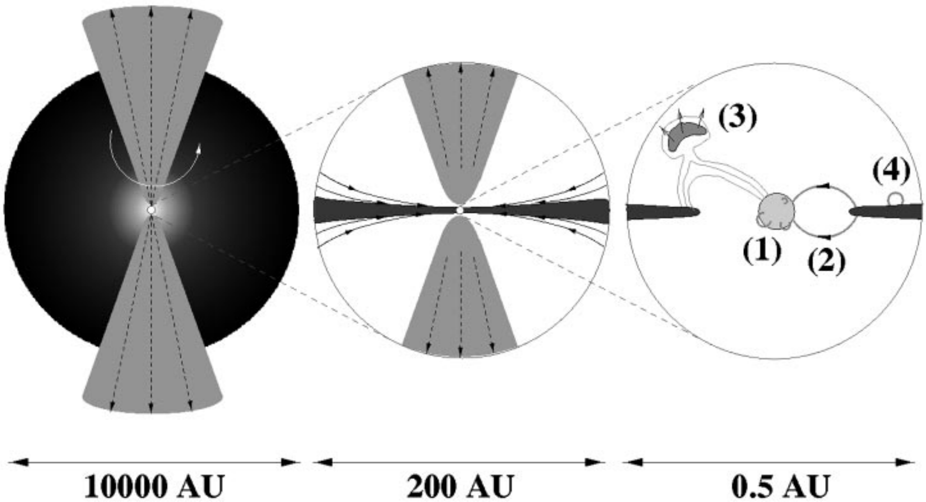


Figure 2 Four magnetic-field configurations that may be responsible for the magnetic activity of Class I protostars. The X rays come from the inner region of a complex structure comprising a collapsing extended envelope (*left*), an inner disk and outflow (*center*), and a star-disk magnetic-interaction region (*right*). (Courtesy of N. Grosso.)

disappear, and we enter the regime of “post-T Tauri” stars. These stars, long missing from YSO samples (Herbig 1978), are now emerging from wide-field X-ray surveys (see Section 6). They are distinguished by their location above the ZAMS (although absence of accurate distances frequently impedes accurate placement on the Hertzsprung-Russell diagram) and by photospheric lithium abundances above those seen in ZAMS stars, because the initial lithium is easily destroyed on the way to the main sequence as a result of convective mixing (Martín 1997).

The interested reader can consult a number of related reviews. Broad treatments of YSOs can be found in *Annual Review of Astronomy and Astrophysics* articles by Shu et al (1987) and Bertout (1989); a monograph by Hartmann (1998); and in conference volumes edited by Lada & Kylafis (1991), Levy & Lunine (1993), and Mannings et al (1999). Various aspects of magnetic activity and flaring in YSOs have been reviewed by Feigelson et al (1991), Montmerle (1991), Montmerle et al (1993), and Glassgold et al (1999). Radio emission is reviewed by André (1996), and recent X-ray results are summarized by Neuhäuser (1997). Some meteoritic implications are discussed by Woolum & Hohenberg (1993).

3. EVIDENCE FOR MAGNETIC ACTIVITY IN YSOs

3.1 Tracers of Magnetic Fields

It is difficult to study YSO magnetic fields directly, and in most cases, indirect tracers of magnetic activity such as cool star spots or high-energy radiation

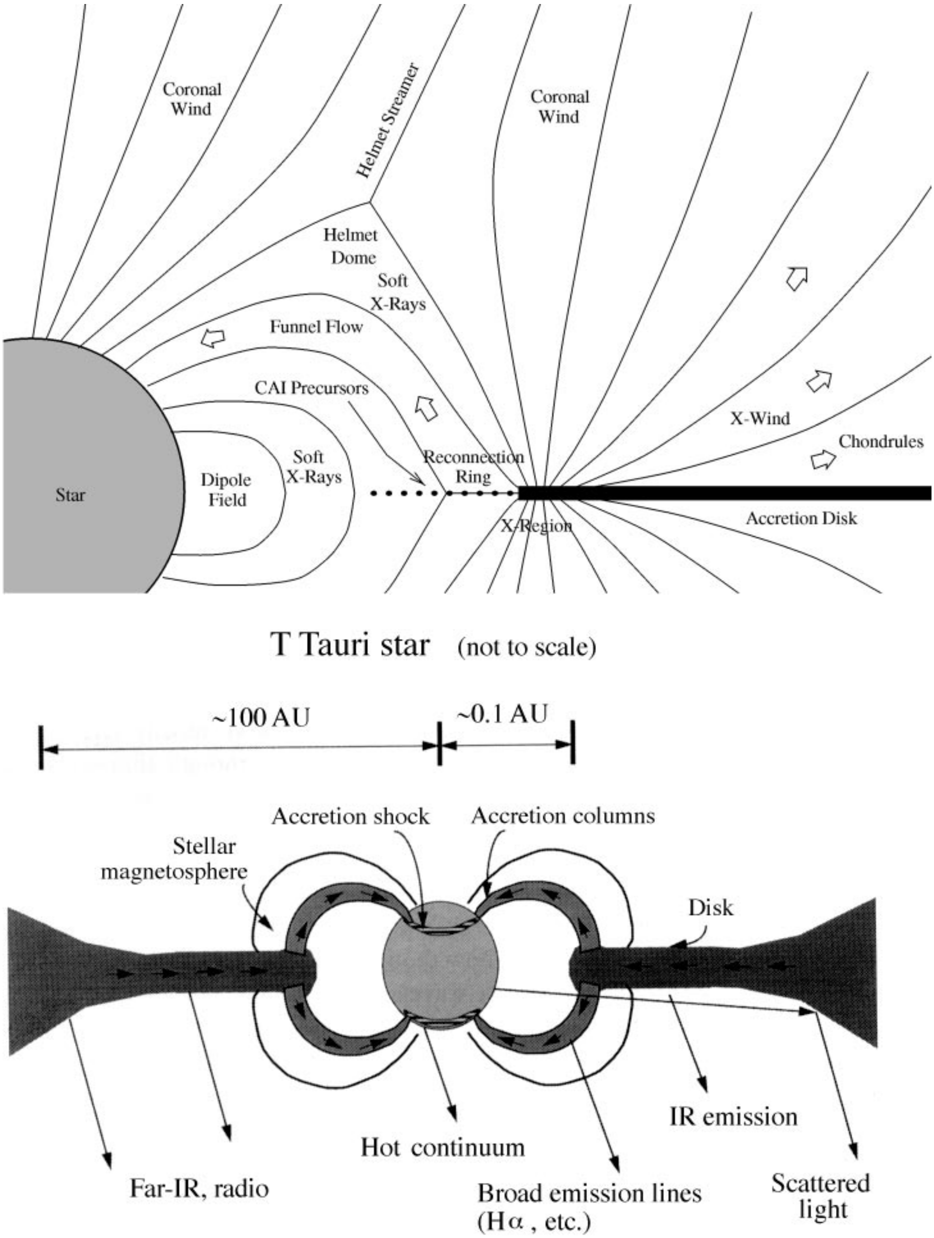


Figure 3 Two contemporary models for Class I–II YSOs, in which magnetic fields play crucial roles: (*top*) the x-wind model of YSOs showing magnetically collimated accretion and outflows with irradiated meteoritic solids (Shu et al 1997); (*bottom*) magnetically funneled accretion streams producing broadened emission lines (Hartmann 1998).

produced by violent field reconnection must be used. Table 1 provides a bibliographic guide to the observational literature on magnetic-activity tracers and is organized by waveband and star-formation regions. We have attempted to be complete in the X-ray and radio listings through 1998, but only a representative selection of the large optical literature is included. The latter includes studies of chromospheres, flares, Zeeman effects, photospheric spots, distances, kinematics, binarity, masses, ages, and other properties of magnetically active YSOs. We briefly examine here what can be learned about the magnetic fields and their reconnection from these observations.

The traditional method for measuring magnetic fields on the surfaces of late-type stars is the detection of Zeeman splitting in magnetically susceptible absorption lines. Applying this method to YSOs has been difficult because of their faintness and (except for WTT/Class III stars) profusion of emission features. Success has recently been achieved in a few cases, indicating fields around 1 to 3 kG covering a large fraction of the photosphere. Photometric and Doppler imaging shows a patchy distribution of large cool star spots, which suggests that the surface fields are complex and multipolar, as in the Sun. These results, however, tell us little about large-scale fields important for star-disk interactions (Figure 2 *right*).

Satellite spectral measurements show that YSO X rays are optically thin thermal bremsstrahlung with associated ionized metal emission lines from multitemperature plasmas with $1 < T_x < 100$ MK (Montmerle et al 1991). The spectral parameters of the emitting plasma—temperature distribution, foreground column density N_H, and metallicity—are similar to those of other magnetically active late-type stars. The importance of flaring is revealed by the X-ray variability. Virtually all YSOs examined at different epochs are variable, and, at any given moment, several percent exhibit luminous flare events with a fast rising curve followed by a slower decay over several hours.

For simple flare models, quantitative properties of the magnetic structures can be inferred from these X-ray flares (e.g. Montmerle et al 1983, Walter & Kuhi 1984). Assuming that radiative cooling dominates conductive cooling in the emitting plasma (and assuming a uniform temperature and density), one can calculate that the plasma density $n_e \simeq 10^{10}$–10^{12} cm^{-3}, which is similar to solar values. The equipartition magnetic field strength $B_{eq}^2/8\pi = 2n_e$kT (which is the minimum possible value for the field strength dynamic flare loops) is approximately 10^2 G.

The morphology of the magnetic structures is a key question that will be raised several times in this review. X-ray flares give information on the emitting volume, not their geometry. If one considers solar-type cylindrical magnetic tubes with length ℓ and aspect ratio approximately 1:10, luminous YSO X-ray flares require $\ell \sim 10^{11}$–10^{12} cm $> R_*$ (note that typically R_* is approximately 2–3 $R_\odot$), if one assumes radiative cooling. If, however, reheating occurs during the flare decline (as is sometimes seen in solar and stellar flares), smaller values may be invoked (Reale et al 1997). However, the magnetic-field morphology may be far more complicated. For example, Skinner et al (1997) consider cooling loops, two-ribbon

TABLE 1 Observational studies of YSO magnetic activity

	X-ray					
Star formation region	**Non-imaging satellites**	***Einstein Observatory***	***ROSAT***	***ASCA***	**Radio**	**Optical**
Orion	1 2 3 4 5 7 16 27 33	6 8 9 11 15 23 26 30	40 41 46 47 48 66 73 75	58 87	8 9 20 21	4 24 25 47 53
Taurus-Auriga		8 9 10 12 14 17 18 20 38 39 58	29 32 44 50 57 61 66 73 82 86	50 69 76 78 82 86	1 2 4 5 11 13 15 18 19 22 23 24 25 27 29 31	2 3 5 7 8 9 10 11 12 15 17 18 19 22 24 27 30 31 37 38 46 48 51 55 57
Ophiuchus	19 24	13 14 17	36 60 66 73	31 62	3 6 12 14 15 16 17 18 19	2 14 59
Chamaeleon		22	26 35 59 66 73 77	85	26	6 21 23 29 36 39
Lupus		8 42	64 71 72 73			6 40 54
Corona Australis		12 17 70	65 73	52	7 28 32	2
Perseus		18	28 55 67 73 79			50
Sco-Cen		33	80		26	20 34 52 56 58
Other		12 21 37	53 54 63 64 66 68 73 74 81 83 88	63	10 17 19 33	2 32 41
Dispersed			35 43 45 48 51 89 90		17 24 27 30	1 13 16 25 28
YSOs			55 59 72 84			31 35 37 42 43 44 45 49

X-ray references: 1 Giacconi et al 1972; 2 White & Ricketts 1977; 3 Cooke et al 1978; 4 den Boggende et al 1978; 5 Bradt & Kelley 1979; 6 Ku & Chanan 1979; 7 Markert et al 1979; 8 Gahm 1980; 9 Feigelson & DeCampli 1981; 10 Feigelson & Kriss 1981; 11 Pravdo & Marshall 1981; 12 Walter & Kuhi 1981; 13 Montmerle et al 1983; 14 Walter & Kuhi 1984; 15 Stone & Taam 1985; 16 Agrawal et al 1986; 17 Walter 1986; 18 Feigelson et al 1987; 19 Koyama 1987; 20 Walter et al 1987; 21 Tagliaferri et al 1988; 22 Feigelson & Kriss 1989; 23 Strom et al. 1990; 24 Koyama et al 1992; 25 Feigelson et al 1993; 26 Pravdo & Angelini 1993; 27 Yamauchi & Koyama 1993; 28 Preibisch et al 1993; 29 Feigelson et al 1994; 30 Gagné & Caillault 1994; 31 Koyama et al 1994; 32 Strom & Strom 1994; 33 Walter et al 1994; 34 Yamauchi et al 1994; 35 Alcalá et al 1995; 36 Casanova et al 1995; 37 Caillault et al 1995; 38 Damiani et al 1995a; 39 Damiani et al 1995b; 40 Gagné et al 1995; 41 Geier et al 1995; 42 Giovannelli et al 1995; 43 Neuhäuser et al. 1995a; 44 Neuhäuser et al. 1995b; 45 Neuhäuser et al. 1995c; 46 Pravdo & Angelini 1995; 47 Preibisch et al 1995; 48 Sterzik et al 1995; 49 Alcalá et al 1996; 50 Carkner et al 1996; 51 Jeffries et al 1996; 52 Koyama et al 1996; 53 Magnani et al 1996; 54 Park & Finley 1996; 55 Preibisch et al 1996; 56 van den Ancker et al. 1996; 57 Wichmann et al. 1996; 58 Yamauchi et al 1996; 59 Alcalá et al 1997; 60 Grosso et al 1997; 61 Gullbring et al 1997; 62 Kamata et al 1997; 63 Kastner et al 1997; 64 Krautter et al 1997; 65 Neuhäuser & Preibisch 1998; 66 Preibisch 1997a; 67 Preibisch 1997b; 68 Schulz et al 1997; 69 Skinner et al 1997; 70 Walter et al 1997; 71 Wichmann et al 1997a; 72 Wichmann et al 1997b; 73 Carkner et al 1998; 74 Gregorio-Hetem et al 1998; 75 Neuhäuser et al 1998; 76 Skinner & Waltner 1998; 77 Neuhäuser & Comerón 1998; 78 Tsuboi et al 1998; 79 Preibisch et al 1998a; 80 Sciortino et al 1998; 81 Hoff et al 1998; 82 Favata et al 1998; 83 Preibisch 1998; 84 Jensen et al 1998; 85 Yamauchi et al 1998; 86 Favata et al 1999; 87 Nakano et al 1999; 88 Naylor & Fabian 1999; 89 Webb et al 1999; 90 Mamajek et al 1999.

Radio references: 1 Bieging et al 1984; 2 Becker & White 1985; 3 Feigelson & Montmerle 1985; 4 Kutner et al 1986; 5 Cohen & Bieging1986; 6 André et al 1987; 7 Brown 1987; 8 Churchwell et al 1987; 9 Garay et al 1987; 10 Becker & White 1988; 11 Bieging & Cohen 1989; 12 Stine et al 1988; 13 O'Neal et al 1990; 14 Leous et al 1991; 15 Phillips et al 1991; 16 André et al 1992; 17 Rucinski 1992; 18 White et al 1992a; 19 White et al 1992b; Felli et al 1993a; 21 Felli et al 1993b; 22 Phillips et al 1993; 23 Skinner 1993; 24 Feigelson et al 1994; 25 Skinner & Brown 1994; 26 Brown et al 1996; 27 Phillips et al 1996; 28 Suter et al 1996; 29 Chiang et al 1996; 30 Carkner et al 1997; 31 Ray et al 1997; 32 Feigelson et al 1998; 33 Stine & O'Neal 1998.

Optical references: 1 Herbig 1973; 2 Herbig & Soderblom 1980; 3 Mundt et al 1983; 4 Smith et al 1983; 5 Rydgren & Vrba 1983; 6 Finkenzeller & Basri 1987; 7 Hartmann et al 1987; 8 Vrba et al 1988; 9 Walter et al 1988; 10 Herbst 1989; 11 Strom et al 1989; 12 Mathieu et al 1989; 13 Pasquini et al 1991; 14 Bouvier & Appenzeller 1992; 15 Feigelson et al 1994; 16 Henry & Hall 1994; 17 Joncour et al 1994; 18 Strassmeier et al. 1994; 19 Strom & Strom 1994; 20 Walter et al 1994; 21 Alcalá et al 1995; 22 Bouvier et al 1995; 23 Gahm et al 1995; 24 Hatzes 1995; 25 Sciortino et al 1995; 26 Sterzik et al 1995; 27 Gullbring et al 1996; 28 Jeffries et al 1996; 29 Lawson et al 1996; 30 Rice & Strassmeier 1996; 31 Wichmann et al. 1996; 32 Bouvier, Forestini & Allain 1997; 33 Covino et al 1997; 34 Feigelson & Lawson 1997; 35 Magazzu et al 1997; 36 Covino et al 1997; 37 Donati et al 1997; 38 Frink et al 1997; 39 Guenther & Emerson 1997; 40 Johns-Krull & Hatzes 1997; 41 Martín 1997; 42 Micela et al 1997; 43 Motch et al 1997; 44 Neuhäuser et al 1997; 45 Sterzik et al. 1997; 46 Strassmeier et al 1997; 47 Alcalá et al 1998; 48 Guenther et al 1999; 49 Guillout et al 1998; 50 Herbig 1998; 51 Johns-Krull et al 1998; 52 Martín 1998; 53 Neuhäuser et al 1998; 54 Wichmann et al 1998; 55 Köhler & Leinert 1998; 56 Preibisch et al 1998b; 57 Luhman et al 1998; 58 Brandner & Köhler 1998; 59 Martín et al 1998.

flares, interbinary flares, and star-disk magnetic reconnection in a discussion of a giant X-ray flare on the Class II–III star V773 Tau. Solar two-ribbon flares (Schmitt 1994, Güdel et al 1999) and rising magnetic arches associated with eruptive solar flares (Svestka et al 1995), which involve complex evolving magnetic geometries and continuous injection of energy, may be valuable analogies for YSO flares.

Radio-continuum flares also provide clues to the magnetic fields in YSOs. The emission, seen in many Class III stars and one Class I object, is highly variable and sufficiently bright to have detectable circular polarization in a few cases. The emission mechanism is quite clearly gyrosynchrotron radiation (as seen in the Sun and in other late-type magnetically active stars), produced by mildly relativistic electrons with energies around 1 MeV spiraling in $\simeq$1 G fields (Dulk 1985). In one dramatic case, linear polarization is also present, which implies electron acceleration up to several MeVs, which has not been seen in other stellar flares (Phillips et al 1996). Simple single-loop models of a rapid radio flare on the Class III star DoAr 21 might indicate a radio loop size significantly larger than X-ray loops (Montmerle et al 1993, André et al 1987).

We proceed with a more detailed presentation of magnetic tracers in YSOs, first by treating the X-ray emission—for which CTT and WTT stars have many features in common—and then by considering separately CTT and WTT properties at other wavelengths.

3.2 X-ray Properties of T Tauri Stars

A typical X-ray image of a nearby ($d < 500$ pc) star-forming region shows dozens (or, for the Orion Trapezium cluster, hundreds) of faint X-ray sources (e.g. Montmerle et al 1983, Strom & Strom 1994, Gagné et al 1995, Preibisch et al 1996; Figure 4). Most of these X-ray sources are associated with Class III WTT stars, but we will refer here to the entire T Tauri population (CTT and WTT) because X-ray properties demonstrate little or no dependence on disk interactions. Repeated imaging shows that most X-ray T Tauri stars vary on time scales of days or longer and, at any given moment, five to ten percent of the stars are caught in a high-amplitude flare with time scales of hours. The X-ray spectra show multitemperature plasma and are often modeled as a soft component with $T_x \simeq 2$–5 MK and a hard component with $T_x \simeq 15$–30 MK, although weak emission at higher temperatures may be present (Preibisch 1997a).

Without the flares, the YSO soft X-ray luminosity function is traced from approximately $10^{28.5}$ to approximately 10^{31} erg s^{-1}. It is difficult to attribute any single average X-ray luminosity to an X-ray population. For example, a particular ROSAT observation of the Chamaeleon I cloud gives a median value of $L_x \simeq 10^{29.4}$ erg s^{-1} for previously identified cloud members (Feigelson et al 1993), $L_x \simeq 10^{29.0}$ erg s^{-1} when X-ray–discovered stars are included (Lawson et al 1996), and a lower value when new low-mass ISO-discovered stars are included (Persi et al 1998). Median luminosities also appear higher when more distant regions (e.g. $d \sim 1$ kpc; Schulz et al 1997, Gregorio-Hetem et al 1998)

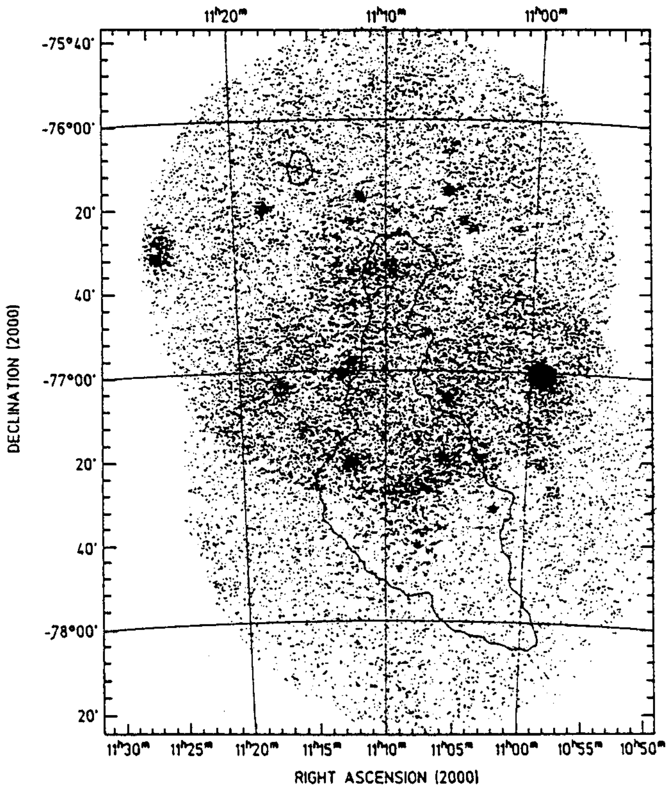


Figure 4 Two ROSAT soft X-ray images of the Chamaeleon I star-forming cloud showing dozens of X-ray–emitting YSOs (Feigelson et al 1993). The contour traces the outline of the cloud from the 100-μm IRAS map.

or less sensitive X-ray data (such as the ROSAT All-Sky Survey) are considered, which is clearly a selection effect.

A number of relationships between X-ray and other stellar properties are found. Most evidently, L_x scales roughly linearly with stellar bolometric luminosity L_{bol}. This relationship is frequently summarized as a constant ratio $L_x/L_{bol} \approx 10^{-4}$ (the exact value depends on the sensitivity and sample definition), which lies well below the rotational saturation level of $L_x/L_{bol} \approx 10^{-3}$ seen in late-type stellar populations (Fleming et al 1989). L_x is also correlated with stellar mass, photospheric temperature, stellar radius, and rotation (e.g. Feigelson 1993). The average T Tauri X-ray luminosity appears to be constant with age or, equivalently, L_x/L_{bol} increases with age (Kastner et al 1997), which implies that the active regions of the stellar surface occupy a roughly constant total area as stars contract. Thus, the X-ray surface flux $F_x = L_x/4\pi R_*^2$ increases with age as stars descend the Hayashi tracks.

The astrophysical origins of these relationships are poorly understood, and it is unclear which relationships represent causal links rather than ancillary statistical dependencies. The only relation expected from standard magnetic-activity theory is between L_x and some rotation indicator—reflecting a more powerful magnetic dynamo in rapidly rotating convective stars—and a link between X-ray surface flux and X-ray temperature ($\sim F_x \propto T_x^2$; Preibisch 1997a), which is expected from standard solar-type magnetic-loop flare models. It is possible, for example, that the L_x mass correlation represents a fundamental connection between YSO surface activity and the incorporation of fossil magnetic fields from the star formation process. The dissipation of such fields by ohmic and turbulent decay can be sufficiently slow that they may be present throughout the T Tauri phase (Tayler 1987).

Large numbers of previously unknown WTT stars appear in X-ray images of nearby star-forming regions (e.g. Feigelson & Kriss 1981, Lawson et al 1996, Neuhäuser 1997), which often increases the catalogued YSO population by factors of two or more (Section 6). However, many well-studied CTT stars are also X-ray luminous. Roughly half of the catalogued CTT stars in Taurus-Auriga and Chamaeleon I clouds are detected in X-ray surveys sensitive to $L_x \simeq 10^{29.0}$ erg s^{-1} (Feigelson et al 1993, Damiani et al 1995a). CTT X-ray properties are similar, if not identical, to those of WTTs. Their X-ray luminosities range from less than $10^{28.5}$ to $10^{30.5}$ erg s^{-1} in the soft X-ray bands, and they are uncorrelated with either Hα luminosity or infrared excess. Their luminosity function sometimes appears slightly diminished compared with that of WTT stars, but that difference can be attributed to low-L_x WTT stars that are not yet identified.

Most CTT X-ray emissions vary by factors of 2 to 10 on timescales of months (Montmerle et al 1983, Walter & Kuhi 1984), and they can occasionally exhibit rapid flares. Figure 5 shows the extraordinary flare in LHα92, reaching 5×10^{32} erg s^{-1} on timescales of an hour. The X-ray plasma temperature rose from about 15 MK during quiescence to 40 MK at the peak during this event (Preibisch et al 1993). A flare with a similar light curve but a more modest peak $L_x \simeq 2 \times 10^{30}$ erg s^{-1} was seen in DD Tau (Strom & Strom 1994). The deeply embedded source SVS 16 in the NGC 1333 star-forming region, which is probably a CTT star, is anomalous: its X-ray emission is constant at a level around 2×10^{32} erg s^{-1}, far higher than the quiescent level of other T Tauri stars (Preibisch 1998).

3.3 Weak-Lined T Tauri Stars

Unresolved radio-continuum emission is seen in several dozen WTT stars at levels of 10^{15} to 10^{18} erg s^{-1} Hz^{-1} or three to six orders of magnitude brighter than powerful contemporary solar flares (e.g. Garay et al 1987, Stine et al 1988, White et al 1992a, Chiang et al 1996). Roughly three-fourths of observed stars are undetected because of instrumental-sensitivity limits; the NRAO Very Large Array has been the most effective telescope. All sources exhibit high-amplitude variability on long time scales, and a few flares on time scales of hours have been caught in two nearby WTT stars, HD 283447 and DoAr 21 (Feigelson & Montmerle 1985,

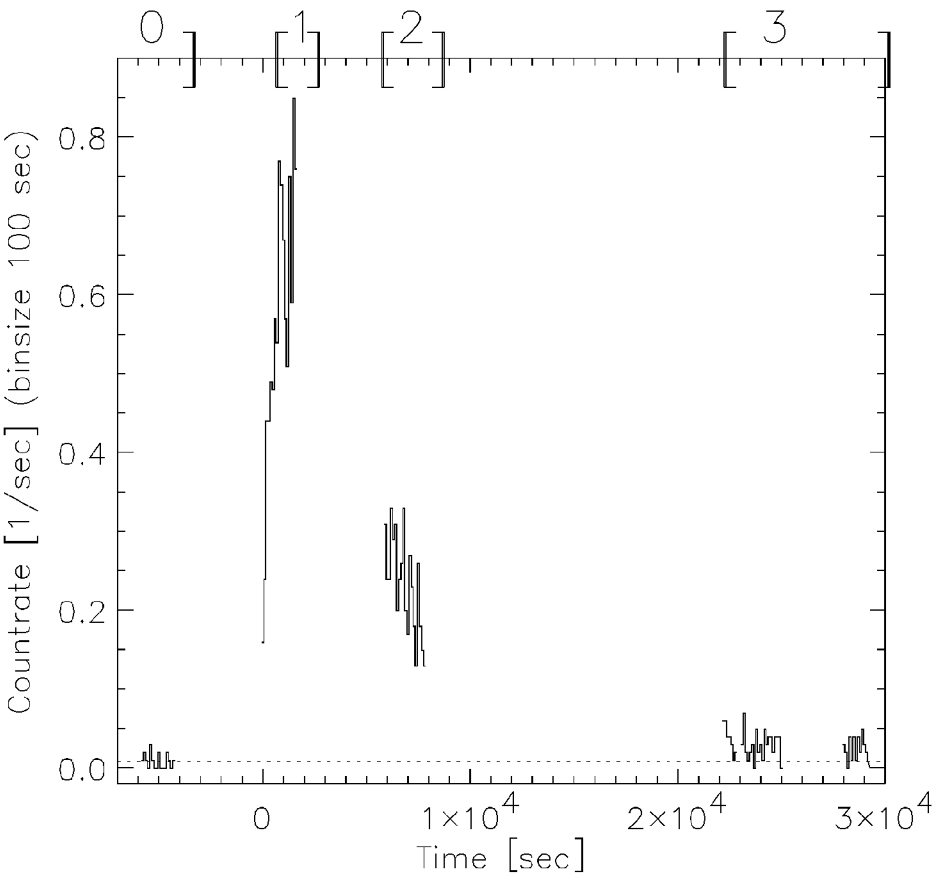


Figure 5 ROSAT light curve of a powerful flare in the Class II CTT star LkHα92 (Preibisch et al 1993).

Phillips et al 1996). Although radio emission from Class I–II objects can be either thermal or nonthermal, the absence of circumstellar disks and ejecta from Class III objects points to a nonthermal mechanism (Montmerle 1991). This possibility is confirmed in several of the stronger sources, in which circular polarization at a level of a few percent is seen (White et al 1992b, Skinner 1993) and VLBI measurements show that the emitting region is too small for thermal processes (Phillips et al 1991). In nearly all respects, WTT radio emission closely resembles that seen in the class of RS CVn magnetically active late-type binary stars.

Optical and UV studies reveal magnetic effects on the stellar surface in several ways. First, a large body of literature from photometric and Doppler imaging studies shows rotational modulations of star spots that cover less than five percent to approximately 50 percent of the surface with temperatures of approximately 500 to 1000 K below the photospheric temperature (e.g. Rydgren & Vrba 1983, Bouvier et al 1995, Joncour et al 1994, Strassmeier et al 1994). The WTT star V410 Tau, for example, has both large high-latitude and low-latitude spots; one large active region may have persisted for more than 1000 rotations (Vrba et al 1988, Rice & Strassmeier 1996). Second, magnetic flares can be seen photometrically or spectroscopically, despite the overwhelming photospheric emission. The X-ray–discovered star V826 Tau exhibited an excursion of $\Delta U = 0.5$ in 40 min (Rydgren & Vrba 1983) and later, a 1-h X-ray flare (Carkner et al 1996). Sudden increases in Balmer continuum and line emission have also been seen with total power around 10^{33}–10^{34} ergs (Gahm et al 1995, Guenther & Emerson 1997). Third, there has been recent success in measurements of Zeeman effects on photospheric absorption lines. Magnetic enhancement of the equivalent width of Fe I lines in the WTT star LkCa 16 is clearly seen and can be interpreted as $B = 2.4$ kG fields covering $f = 0.6$ of the stellar surface (Guenther et al 1999). Spectropolarimetric observations have detected fields in V410 Tau, HD 283472, and HD 155555 (Donati et al 1997).

To illustrate the interwoven phenomenology of magnetic activity at different wavelengths, we briefly describe the most active T Tauri star in the Taurus-Auriga cloud complex, HD 283447 = V773 Tau (Feigelson et al 1994, Phillips et al 1996, Skinner et al 1997, Tsuboi et al 1998). It is a hierarchical triple system comprising a K2–K3 close binary and a distant K3 companion. The close binary has $L_{\rm bol} \simeq 5\, L_\odot$, age 1 Myr, and rapid rotation with $v \sin i = 44$ km s^{-1} and $P_{\rm rot} =$ 3.4 days. The system has a truncated circumstellar disk and very faint broad Hα emission and thus might be considered an intermediate WTT/CTT object. About 17 percent of the surface is covered with a rotationally modulated cool spot, and the MgII chromospheric emission is strongly elevated. The continuous quiescent X-ray emission from the system is unusually strong with $L_{\rm x} \simeq 1 \times 10^{31}$ erg s^{-1}, and the star repeatedly exhibits powerful day-long flares with peak $L_{\rm x} \simeq 2 - 10 \times 10^{32}$ erg s^{-1} with peak plasma temperatures of more than 100 MK. Both inner companions are radio loud. The centimeter radio emission is highly variable at around several times 10^{17} erg s^{-1} Hz^{-1}. Unique among late-type stars, the emission exhibits both circular and linear polarization, which indicates electron acceleration to energies significantly more than one MeV. The unusually high levels of magnetic activity in V773 Tau might be attributed to the early loss of its interacting disk, which left the star with a rapid rotation rate and consequently strong magnetic dynamo. Similar systems include V410 Tau and HDE 283572 in Taurus-Auriga (Rice & Strassmeier 1996, Walter et al 1987), DoAr 21 in Ophiuchus (Feigelson & Montmerle 1985), and Par 1724 in Orion (Neuhäuser et al 1998).

The more typical solar-mass WTT star, however, is 2–20 Myr old with slow rotation ($P_{\rm rot} > 10$ days), $L_{\rm x} \simeq 10^{28.5}$–$10^{29.5}$ erg s^{-1}, no known X-ray flares, and undetectable radio emission or photometric spots. By studying the initial mass function, we know that the most common Class III stars must be pre–main-sequence M stars with $M_* \sim 0.2 - 0.6\, M_\odot$ and that significant numbers of brown dwarfs exist. Because of the (unexplained) $L_{\rm x}$-mass correlation, these brown dwarfs are underrepresented in existing X-ray studies. At least two brown dwarfs have been detected in X rays to date at low levels (Neuhäuser et al 1999).

WTT stars extend empirical relations between magnetic activity tracers seen in older solarlike stars. A sample of 1 $M_\odot$ main-sequence stars with a wide range of ages shows several consistent patterns: As one moves from the oldest disk population to ZAMS stars, radio luminosity rises by 10^4, X-ray luminosity rises by 10^3, and the fraction of plasma at $T_x > 10$ MK rises by 10^2 in emission measure (Gudel et al 1997). These trends are explained by a scaling of magnetic activity with rotational velocity, in which X-ray (but not radio) luminosity is limited by saturation at the stellar surface and average plasma temperatures rise with increased fraction of plasma in microflares rather than in the quiescent corona. Although the data are still fragmentary, T Tauri stars appear to follow this pattern: X-ray luminosities are generally below saturation levels and their L_r/L_x ratios and average plasma temperatures are several times higher than in ZAMS stars (Skinner & Walter 1998).

3.4 Classical T Tauri Stars

In contrast with WTT stars, evidence for CTT magnetic activity at non–X-ray wavebands is sparse. A few CTT stars are detected in continuum at centimeter wavelengths (e.g. LkHα101, DG Tau, T Tau North), but this emission is caused by thermal bremsstrahlung in partially ionized winds (Cohen & Bieging 1986). The apparent absence of nonthermal radio emission in CTTs may not mean that they are magnetically inactive. André (1987) convincingly argues that, under reasonable assumptions of ionization and geometry, YSO winds are more than sufficiently dense to free-free absorb nonthermal radio-continuum emissions produced close to the star.

In the optical band, the manifestations of magnetic activity seen in WTT stars are intermixed with the powerful effects of star-disk interactions such as emission lines, hotspots, continuum veiling, and high-amplitude aperiodic photometric variations (Smith et al 1999). For example, BP Tau shows complex emission line variations that are more readily interpreted in terms of magnetically channeled accretion hotspots than of magnetic reconnection flares (Gullbring et al 1996). However, valuable results have emerged from studies of CTT stars that have relatively weak winds and veiling but still show indications of star-disk interactions. Doppler imaging of the CTT/WTT star Sz 68 reveals near-polar star spots several hundred degrees cooler than the photosphere (Johns-Krull & Hatzes 1997). The inferred spotted surface is similar to that seen in WTT stars but is accompanied by variable red-shifted Hα and Na I D absorption likely to be caused by a magnetospheric accretion flow. Magnetic activity in Sz 68 is also evident from its X-ray emission at $L_x \simeq 6 \times 10^{29}$ erg s^{-1} (Krautter et al 1997).

Efforts to detect direct manifestations of magnetic fields in CTT optical-infrared spectra have recently borne fruit. The spectrum of BP Tau shows broadening in the Zeeman-sensitive Ti I line at 22.2 μm, corresponding to a total magnetic flux of $Bf \simeq 3.3 \pm 0.3$ kG (Johns-Krull et al 1999). Enhancements in equivalent widths of photospheric lines sensitive to the Zeeman effect have been found in the CTT star T Tau North and CTT/WTT star LkCa 15, indicating fields of $Bf \simeq 2.5$ and 1.4 kG, respectively (Guenther et al 1999). These field strengths are comparable with those of solar active regions but cover large fractions of the stellar surface.

The simplest conclusion we can draw is that CTT stars are magnetically very similar to WTT stars. The X-ray emission and flaring, the X-ray loop sizes, and the photospheric magnetic fields inferred from Zeeman effects seem largely unaffected by the complex star-disk interactions that produce a complex combination of accretion and outflows. The absence of radio gyrosynchrotron emission can be explained as an absorption effect, combined with smaller magnetic radio loops. It is thus tempting to conclude, by analogy with WTT stars where the multiwavelength data are more complete, that CTT stars are basically characterized by enhanced solar-type magnetic activity and do not exhibit any radical differences in magnetic geometries or behaviors.

3.5 Protostars

Detection of X rays from magnetic activity in Class I or 0 stars is inherently very difficult; these YSOs are almost always deeply embedded in their nascent molecular clouds, are surrounded by infalling envelopes and outflowing jets, and may be additionally obscured by their circumstellar disks. Typical extinctions from these components are $10 \leq A_V \leq 50$ for Class I sources and may reach $A_V \simeq 1000$ for Class 0 sources. Nonthermal radio emission is not absorbed by intervening cold material but is likely to suffer free-free absorption from ionized gas associated with the base of bipolar outflows, as in CTT stars (André 1996). Such gas is shown to be frequently present by elongated radio-continuum structures associated with the YSOs producing Herbig-Haro objects (Rodríguez 1997).

In light of these observational difficulties, evidence for protostellar magnetic activity did not emerge until the mid-1990s (Table 2). The first indication was the tentative report of several Class I stars among the dozens of faint X-ray sources found in a deep ROSAT exposure of the rich YSO cluster in the ρ Ophiuchi cloud, which was later confirmed with ASCA satellite observations (Casanova et al 1995, Kamata et al 1997). Unequivocal X-ray detection of a cluster of Class I sources emerged from an ASCA study of the Corona Australis cloud core (Koyama et al 1996). Remarkably, these sources were seen in the 4- to 10-keV band, whereas the T Tauri stars in the same field were found only in the 0.5- to 2-keV band (Figure 6). Note, however, that these detections probably represent the most magnetically active protostars, as most of the protostars falling in ROSAT PSPC fields are not detected at these levels (Carkner et al 1998).

Several protostars exhibit quite extraordinary X-ray properties that distinguish them from T Tauri and other late-type stars. The strongest X-ray source in the Corona Australis cloud core is likely (although crowding raises some doubt) associated with the extremely young Class 0–I YSO CrA IRS 7, which exhibited a flare similar to those seen in T Tauri stars but with a spectrum extended to 10 keV and with a strong and curiously broadened iron emission line complex around 6 to 7 keV (Figure 6; Koyama et al 1996). YLW 15 in the ρ Ophiuchi cloud core,

TABLE 2 X-ray detected protostars

Cluster	Source	A_V^a	Detector	L_x^b	Variability	Ref.[c]
R CrA	IRS1 (TS2.6)	19†	SIS	3	—	1
			PSPC	3	—	2
	IRS2 (TS13.1)	19†	SIS	2	—	1
			PSPC	9	—	2
			HRI	4	—	2
	IRS5 (TS2.4)	19†	SIS	3	—	1
			PSPC	5	—	2
	IRS7 (R1)	19†	SIS	$\rightarrow 12$	Flare	1
	IRS9 (R2) ?	19†	SIS	2	—	1
ρ Oph	YLW15 (IRS43)	56*	PSPC	160	—	3
		30*	HRI	$\rightarrow 10^{3-5}$	Flare	4
		15†	SIS	150	Periodic?	5
	EL29	17†	SIS	$3 \rightarrow 54$	Flare	6
	IRS44	52*	PSPC	<80	—	3
		13†	SIS	$3 \rightarrow 10$	Flare?	6
	IRS46	37*	PSPC	<20	—	3
		13†	SIS	$3 \rightarrow 11$	Flare?	6
	WL6	22†	SIS	3 – 14	Periodic?	6
Cha I	Ced110 IRS6	30*	PSPC	2	—	7
Orion	SSV63	50*	SIS	$80 \rightarrow 720$	Flare	8

[a]Visual absorption in magnitudes estimated from infrared colors (*) or from the X-ray spectrum (†).

[b]L_x is given in units of 10^{30} erg s^{-1} cm^{-2} for the energy range of the detector: 0.1–2.4 keV for ROSAT PSPC and HRI; 0.5–10 keV (ref. 2) and 2–10 keV (ref. 5) for ASCA SIS. Arrows point to the peak luminosity of flares.

[c]References:

1. Koyama et al 1996
2. Neuhaüser & Preibisch 1997
3. Casanova et al 1995
4. Grosso et al 1997
5. Tsuboi et al 1999 (submitted for publication)
6. Kamata et al 1997
7. Carkner et al 1998
8. Ozawa et al 1999 (submitted for publication)

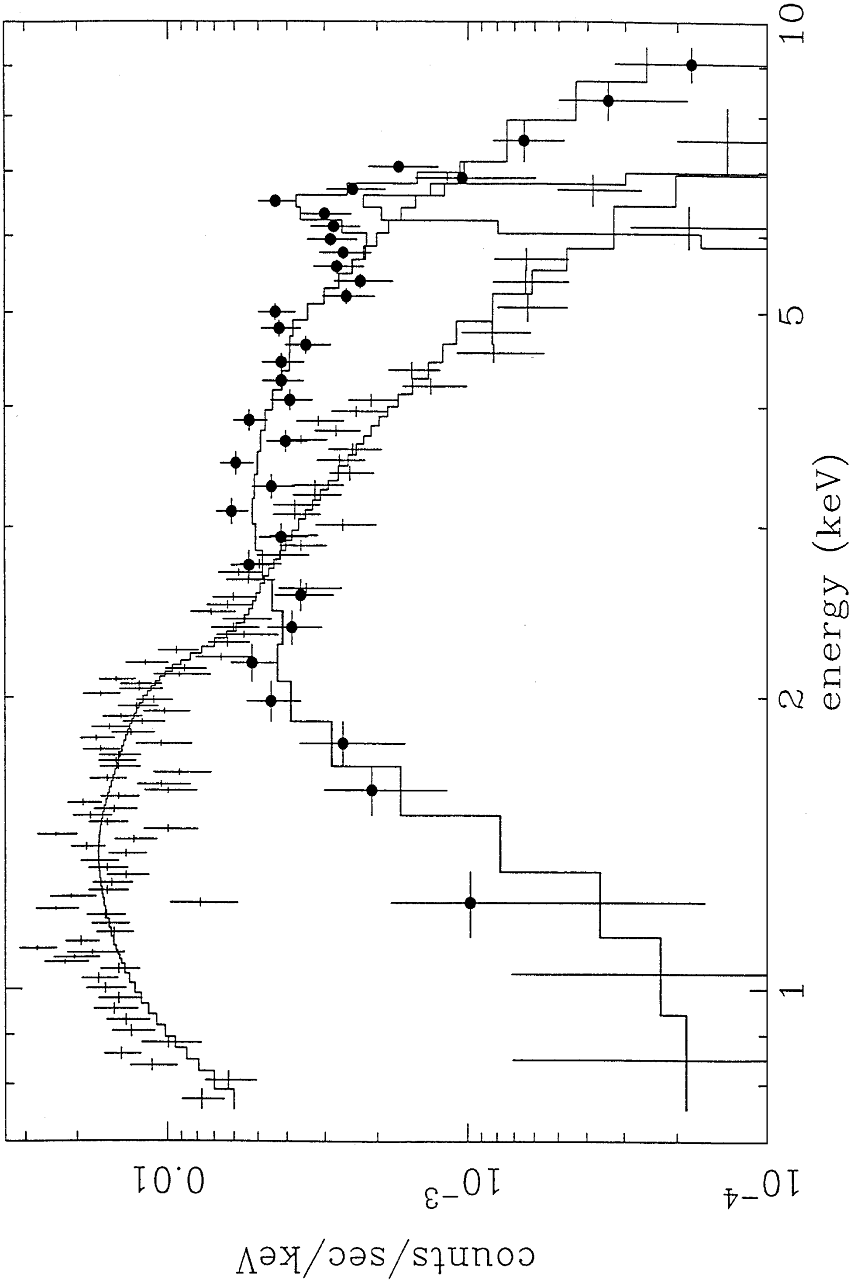


Figure 6 ASCA spectrum of a hotter absorbed Class 0–I protostars (*filled circles*) and a cooler unabsorbed Class III WTT star in the Corona Australis cloud core (Koyama et al 1996).

a luminous and heavily obscured Class I protostar, exhibited a powerful X-ray flare with a 5-h decay in a ROSAT HRI observation. Depending on the unknown plasma temperature and uncertain absorption ($A_V \sim 30$), this event reached a peak $L_x \sim 10^{33}$–10^{35} erg s^{-1}, perhaps the most powerful X-ray flare ever seen in a late-type star (Grosso et al 1997). The associated sizes for the magnetically confined plasma are of order 0.1 AU for this event. It is possible that such superflares were responsible for enigmatic variations seen years earlier with nonimaging Tenma and Ginga satellite observations of the ρ Ophiuchi cloud, with a total unresolved emission of $L_x \sim 10^{32}$ erg s^{-1} (Koyama 1987, Koyama et al 1992). Last, one of a dense group of heavily embedded ($A_V \simeq 30$) infrared sources in the Serpens cloud core, which are likely to be protostars, was found to have $L_x \simeq 10^{32.5}$–$10^{33.5}$ erg s^{-1} in each of two ROSAT observations separated by 2.5 years (Preibisch 1998). This finding may be the most luminous level of quiescent X-ray emission yet seen in a YSO.

Although only one tentative Class 0 source in X rays has been detected to date (CrA IRS 7; Koyama et al 1996), it is unclear whether X-ray emission or other magnetic activity indicators are present at this early stage. Class 0 protostars produce unusually powerful outflows (Bontemps et al 1996), but they could be collimated by nonmagnetic mechanisms (Henriksen et al 1997). It is also conceivable that high-energy processes occur far from the central protostar, caused by the compression and reconnection of magnetic fields in the collapsing envelope (Norman & Heyvaerts 1985).

Very Large Array studies demonstrate that protostars typically exhibit extended thermal radio-continuum emission at the same luminosity levels as seen in WTT stars, 10^{15}–10^{17} erg s^{-1} Hz^{-1} (Anglada 1996). This emission pattern is attributed to shock-induced ionization at the base of the outflow. However, two unusual cases of nonthermal radio-continuum emission from protostars have been found. First, T Tau South, the infrared companion to the optically bright CTT prototype T Tau North, has circularly polarized centimeter wavelength emission. T Tau South has been spatially resolved into two lobes of opposite helicity with the MERLIN interferometer on a scale of 10 AU (Ray et al 1997). This result may arise from magnetic shocks and particle acceleration in the bipolar outflow. (A linearly polarized triple-radio source associated with a protostar in Serpens may have a similar origin; Henriksen et al 1991.) The second case, the X-ray–emitting IRS 5 in the Corona Australis cloud, more closely resembles a magnetically active WTT. Its centimeter emission is 10^{16}–10^{17} erg s^{-1} Hz^{-1}, varying by factors of 2–10, and its circular polarization fraction jumped from 10 to 37 percent in a day (Feigelson et al 1998). CrA IRS 5 does not appear to be powering an outflow, so its environment may be relatively free of absorbing ionized material.

With optical/UV band studies precluded by obscuration, and only a handful of cases with detected X-ray and nonthermal radio emission, our knowledge of protostellar magnetic activity is still fragmentary. There are nonetheless tantalizing suggestions that protostellar X-ray flares can be more powerful and can produce hotter plasma temperature components than seen in T Tauri flares.

4. ORIGIN OF THE MAGNETIC ACTIVITY

From the observations outlined here, we can distinguish three lines of evidence for magnetically generated high-energy processes in YSOs: X-ray emission with high levels of continuous emission and powerful 10^4-s flares of $T \simeq 10^6$ to 10^8 K plasma; gyrosynchrotron radio-continuum emission and flares from MeV electrons spiraling along large-scale and well-ordered magnetic-field lines; and various optical studies (photometric and Doppler reconstructed star spots, spectroscopic chromospheric indicators, Zeeman line broadening, and photometric and spectroscopic flares) demonstrating that photospheric surfaces have elevated magnetic fields and associated active regions and flares. The X-ray and radio observations provide explicit evidence for high-energy photons and particles, which probably can be produced only in explosive magnetic reconnection events and confined in closed large-scale magnetic structures.

Together, these lines of evidence suggest that magnetic fields rooted at the stellar surface are responsible for the observed flaring. This reasoning led to the model of YSOs as enhanced solar-type magnetic activity (e.g. Montmerle et al 1983, Feigelson et al 1991). The magnetic activity of CTT stars appears similar in most respects, although most characteristics are masked by the signatures of accretion and wind ejection. Alternative models, such as CTT X rays arising from the release of gravitational energy in magnetic accretion columns (Lamzin et al 1996) or from colliding CTT winds (Zhekov et al 1994), cannot account for the hard X-ray spectra or the lack of correlation between X-ray and optical variability and between X-ray and emission lines.

Enhanced solar-type magnetic activity is not surprising in cool stars with deep convection zones and relatively rapid rotation, because a magnetic dynamo should be active unless the star rotates like a solid body. For the quiet Sun, the large-scale magnetic structure can be explained—and analytically computed without a dynamo—combining an azimuthal equatorial-current sheet and an axisymmetric multipole field representing the internal magnetic field (Banaskiewicz et al 1998). The most popular theory, the α-ω dynamo, combines convection and differential rotation to amplify fields, which then erupt through the surface and produce the observed magnetic tracers described above (Gilman 1983). This model is an important element in successfully explaining various solar phenomena such as the butterfly diagram and convective amplification of photospheric fields. Although the dynamo mechanism probably also operates on late-type stars, no detailed calculations or models exist for YSOs. Strictly construed, the standard α-ω dynamo breaks down for fully convective T Tauri stars. It is also disturbing that the available T Tauri data show rather noisy correlations between L_x-rotation diagrams. The current evidence for enhanced solar-type magnetic activity in YSOs is thus based more on empirical analogies than astrophysical insights.

The solar-type activity interpretation of high-energy emission in the earlier YSO stages is under challenge, mainly by growing arguments for field structures far larger than those seen on the Sun. Recent models of Class I–II systems require that stellar magnetic fields have a strong bipolar component that extends out several stellar radii, where it couples to the disk at the star-disk corotation radius, which is typically around 3 to 10 R_* from the stellar surface (e.g. Königl 1991, Shu et al 1994, Ferreira & Pelletier 1995, Paatz & Camenzind 1996, Spruit et al 1997). These models have considerable explanatory power, accounting for the generation of winds and collimated outflows (Figure 3 *top*), the distribution of YSO surface rotational velocities (Cameron & Campbell 1993, Armitage & Clarke 1996, Li 1996, Bouvier et al 1997), and the unusual shape of the broad optical emission lines as magnetically funneled accretion streams (Hartmann et al 1994, Figure 3 *bottom*). The real situation, however, is likely to be far more complex than YSO models based on dipole magnetic geometry and steady-state assumptions (Safier 1998). For example, time-dependent MHD numerical calculations illustrate rapid changes of any initial magnetic field configuration within a few disk orbital periods (Miller & Stone 1998).

From a broad perspective, we can consider four possible magnetic geometries in YSOs (Figure 2, *right panel*):

1. Solar-type multipolar fields with both footprints rooted in the stellar photosphere. As in the Sun, reconnection would arise from differential rotation and convection under the photosphere. This model is well adapted to the WTT and CTT stars. The fields might be generated by an α-ω-type dynamo, or might be "fossil fields" inherited from the parent molecular cloud.
2. Field lines connecting the star to the circumstellar disk at its corotation radius. This configuration is supported by models of rotational spindown (e.g. Königl 1991, Edwards et al 1993), magnetically funneled accretion, and collimated outflows in CTT stars. Here, reconnection occurs in field lines near but not directly at the corotation radius, perhaps because of the passage of accretion inhomogeneities through the disk (Shu et al 1997). There is also the possibility of reconnection inside the corotation radius if the star is still rotating rapidly with respect to the inner disk. This may be the case for young protostars before magnetic braking is complete. The quasi-periodic X-ray flares in the Class I protostar YLW 15 may arise from such a situation (Tsuboi et al 1999).
3. Field lines above the corotation radius. Two-dimensional, time-dependent MHD calculations of a stellar field threading a Keplerian circumstellar disk predict that plasmoids filled with X-ray–emitting gas will be ejected away from the disk by reconnection events caused by star-disk differential rotation (Figure 7; Hayashi et al 1996).
4. Magnetic loops with both feet in the disk. The combination of differential rotation and convective motions within the circumstellar disk may produce a self-amplifying magnetic dynamo in the disk. Magnetized disk models of

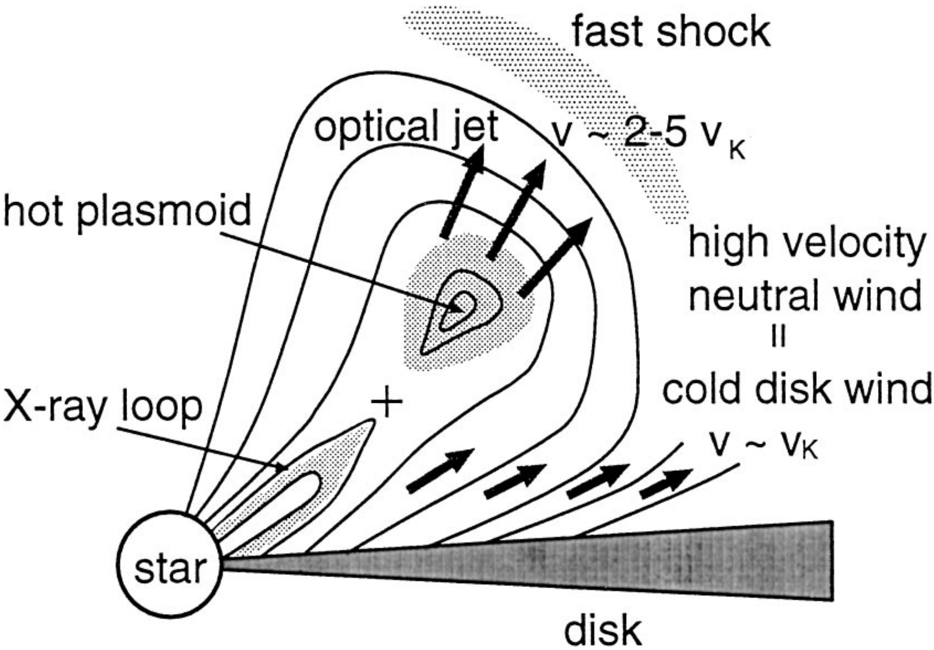


Figure 7 The result of an MHD calculation of magnetic reconnection and plasmon ejection above the star-disk corotation radius in a YSO (Hayashi et al 1996).

this type have been discussed in the contexts of both astrophysical disks (e.g. Field & Rogers 1993, Romanova et al 1998) and the solar nebula, in the context of meteoritics (Levy & Araki 1989; also see Section 5.3).

A fifth possible configuration can be imagined involving magnetic connections between companions in short-period binary YSOs. However, only a small fraction of YSOs reside in binaries such as RS CVn systems, in which the orbits are sufficiently small for this possibility to be considered (Mathieu 1994). RS CVn magnetic activity is usually explained by individually enhanced fields produced by internal dynamos caused by tidally locked rapid rotation, whereas, in YSOs, the rotation is inherited from the star formation process (either directly or through a disk). Therefore, binarity is not expected to play an important role in explaining the magnetic activity of YSOs.

Option 1 has been extensively studied in the solar context, and is the basic explanation for magnetic activity in older late-type stars such as dMe and RS CVn binary stars. For YSOs, the possibility of disk-based fields (options 2–4) has been the subject of considerable recent, detailed study. The geometry of star-disk fields depends critically on the magnetic resistivity of the disk: a fully ionized disk will tend to exclude external fields, whereas a neutral disk will be fully threaded but uncoupled from such fields (Miller & Stone 1998). Outflows may be accelerated along open stellar poloidal field lines by complex interactions at the star-disk field boundary and/or by disk poloidal fields (e.g. Blandford & Payne 1982, Uchida & Shibata 1984, Shu et al 1994, Hirose et al 1997, Ouyed & Pudritz 1997, Kudoh & Shibata 1997, Shang et al 1998). Time-dependent MHD calculations of the star-disk field interaction (Figure 7) show a sequence of twisting of closed stellar field lines, current sheet formation, reconnection, and ejection of a magnetic island with plasma heated to $\leq 10^8$ K, consistent with X-ray flare observations (Hayashi et al 1996; Goodson et al 1997). The plasma physics of one specific magnetic reconnection process—the resistive tearing instability—has been investigated in this context, and this process shows growth rates on time scales of hours (Birk 1998). If field lines thread the disk at different disk radii, differential rotation will cause twisting and reconnection, perhaps leading to a perpetually X-ray–emitting, flaring disk corona (Tout & Pringle 1996, Romanova et al 1998). Given that resulting X rays are likely to promote ionization and turbulence in the disk (see Section 5.1), it seems plausible that this situation may commonly occur.

We conclude that magnetic reconnection processes occur very frequently in YSOs. The fundamental conditions for reconnection, continual displacement of magnetic footprints, is even more likely to occur in YSOs than in other stellar situations due to the many possible magnetic configurations offered by star-star, star-disk, and disk-disk interactions.

5. EFFECTS ON THE CIRCUMSTELLAR AND INTERSTELLAR ENVIRONMENT

Because YSOs are surrounded by circumstellar gas and dust and may be deeply embedded in molecular cores (at least in their early stages of evolution), X rays will induce a variety of effects, including ionization, heating, and modification of gas chemistry and dust grain composition. The issues outlined here are reviewed in more detail by Glassgold et al (1999).

5.1 X-ray Ionization

X-ray ionization of a fraction of the primarily molecular gas within and around YSOs is particularly important because of its role in coupling gas and magnetic fields. Unlike high-mass YSOs emitting copious UV photons, which create a fully ionized HII region terminated by a thin transition region, a low-mass YSO emitting X rays produces an extended region of low ionization and X-ray heating. The effects of the X rays gradually become negligible because of absorption by intervening material and geometric dilution. Research on these X-ray dissociation regions began many years ago (e.g. Dalgarno & McCray 1972, Halpern & Grindlay 1980, Lepp & McCray 1983, Krolik & Kallman 1983) and has recently undergone a vigorous renewal.

The most important X-ray ionization process of cold material is photoionization of the inner K and L shells of heavy elements: a ∼1-keV photoelectron is generated, which produces a cascade of secondary electrons that are responsible for most subsequent ionizations in the medium. The mean energy to create an ion pair in a cosmic abundance gas is approximately 35 eV, so that approximately 30 secondary electrons are created by an initial 1-keV photoelectron. The atomic structure of the heavy atom rearranges itself with the ejection of a few Auger electrons and fluorescent photons (Kaastra & Mewe 1993). In addition, X rays with $E_x > 2$ keV can ionize when they scatter through a large angle (Halpern & Grindlay 1980), an effect known as Compton ionization. The energy transfer is much smaller than in the photoelectric effect, especially for the heavy atoms responsible for most of the absorption cross-section, and Compton energy losses do not become competitive until $E_x \sim 20$ keV.

The total photoionization cross-section decreases rapidly with photon energy, roughly as $\sigma \propto E_x^{-2.5}$. It also depends on the atomic weight of the material as $\sigma \propto Z^3$. In a gas with cosmic abundance, most of the ionizations occur in light atoms (H and He); but metals are responsible for the absorption of higher-energy X rays. For 1-keV photons, the optical depth is unity for a hydrogen column density of $N_H \simeq 4.4 \times 10^{21}$ cm^{-2}, which, for a normal interstellar dust-to-gas ratio, is equivalent to $A_V \simeq 2$ or $A_J \simeq 1$ (Ryter 1996). Therefore, 5-keV photons, which are detected in YSOs with the ASCA satellite, can penetrate to $A_V \simeq 100$ and thus have a potential effect even in deeply embedded environments.

The principal competing source of ionizing radiation in the vicinity of YSOs is ambient UV starlight, which dominates the outer $A_V \simeq 3$ regions of star-forming clouds and galactic cosmic rays, which produce $\approx 10^{-17}$ ionizations s^{-1} (McKee 1989). The cosmic-ray ionization rate, which corresponds to ionization fractions of $\approx 10^{-9}$ throughout cloud interiors, is particularly uncertain; for instance, low-energy cosmic rays may be excluded from dense cloud cores by magnetic scattering (Lepp 1992). For a typical YSO with $L_x = 10^{29}$ erg s^{-1} and photon energies of approximately 1 keV, the total X-ray ionization may (depending on intervening absorption) dominate cosmic-ray ionization out to distances $r_{max} \approx 0.02\, L_x/(10^{29}$ erg s$^{-1})$ pc $\sim$ 4000 AU (Krolik & Kallman 1983, Glassgold et al 1999).

The X-ray ionization effects in the molecular cloud environment may be considerably greater than this estimate because the recombination time scale is approximately 10^1 years, considerably longer than the $<10^1$-year timescale of flare recurrence in YSOs. For cloud ionization, the episodic YSO flares appear essentially as a continuous high-intensity process. Thus, a single YSO with flare luminosities around 10^{30}–10^{31} erg s^{-1} may be the dominant source of ionization for a 0.1-pc cloud core (Glassgold et al 1999). Note that the low ionization fractions involved are sufficient to couple the neutral matter with any magnetic fields and require ambipolar diffusion for gas passage through the field (e.g. Ciolek & Mouchovias 1995).

On smaller spatial scales, the implications of YSO X-ray ionization for circumstellar disks have recently been calculated by Glassgold et al (1997) and Igea &

Glassgold (1999). They consider a model disk similar to the solar nebula illuminated by an X-ray source elevated a few stellar radii above the corotation radius (Figure 3 *top*). Figure 8 shows the ionization of X rays at various energies in terms of the column density of the disk measured perpendicularly from its surface, N_{perp}. These particular curves were calculated at a radial distance of 1 AU from the star. YSO X rays penetrate to some distance towards the midplane in the inner disk, whereas they reach all disk material in the outer disk. The inner disk thus has a midplane neutral dead zone surrounded by an ionized zone (Gammie 1996).

Although the resulting disk ionization level is always low, the YSO X rays impact a far larger volume in the disk than is ionized by cosmic rays. The X-ray ionization will couple the disk material to magnetic fields and MHD processes. In particular, this weakly ionized differentially rotating disk is thought to stimulate the Balbus-Hawley magnetorotational instability (Balbus & Hawley 1991), which will induce an MHD turbulent viscosity and promote flow towards the inner boundary of the disk (Gammie 1996). By this means, YSO X rays may regulate the supply of material accreting onto the protostar and for ejection in high-velocity winds, Herbig-Haro jets, or FU Orionis outbursts.

In an analogous fashion, X-ray ionization may be important for the coupling between disk and outflow required for outflow acceleration. Models of highly collimated Herbig-Haro jets and weakly collimated molecular bipolar flows often require that the rotational energy of the disk be converted into a radial acceleration by some kind of magneto-centrifugal process (Königl & Ruden 1993, Pudritz et al 1999). No calculations of the X-ray effects on outflow physics have been made to date.

5.2 X-ray Effects on Ambient Chemistry and Dust

X-irradiation of molecular gas will produce a complicated sequence of chemical reactions of molecular material at various distances within and around YSOs (e.g. Krolik & Kallman 1983, Maloney et al 1991, Lepp & Dalgarno 1996, Yan & Dalgarno 1997, Aikawa et al 1998). The detailed consequences are quite difficult to calculate in a fully self-consistent model, and they depend on the assumed chemical reaction network. In the warmer regions, a variety of neutral reactions are promoted by X-ray heating of the gas, whereas in cooler regions the X rays stimulate molecular synthesis by ion-molecule reactions.

Kastner et al (1997) report possible evidence for X-ray–induced chemistry in the disk of the nearby ($d \simeq 50$ pc) CTT star TW Hya. They attribute the high CN/HCN ratio and HCO^+ abundance to X-ray illumination. The isotopes of HCO^+ have long served as tracers of electron fractions in molecular clouds; HCO^+ itself may be destroyed near the X-ray source by dissociative recombination with electrons, as observed in the molecular cloud close to the microquasar 1E1740.7–2942 (Yan & Dalgarno 1997). In YSO environs, X-ray ionization can thus be probed with high-resolution millimeter interferometers. Other potentially observable tracers of X-ray–induced chemistry are located in the far-IR and include the 149-μm

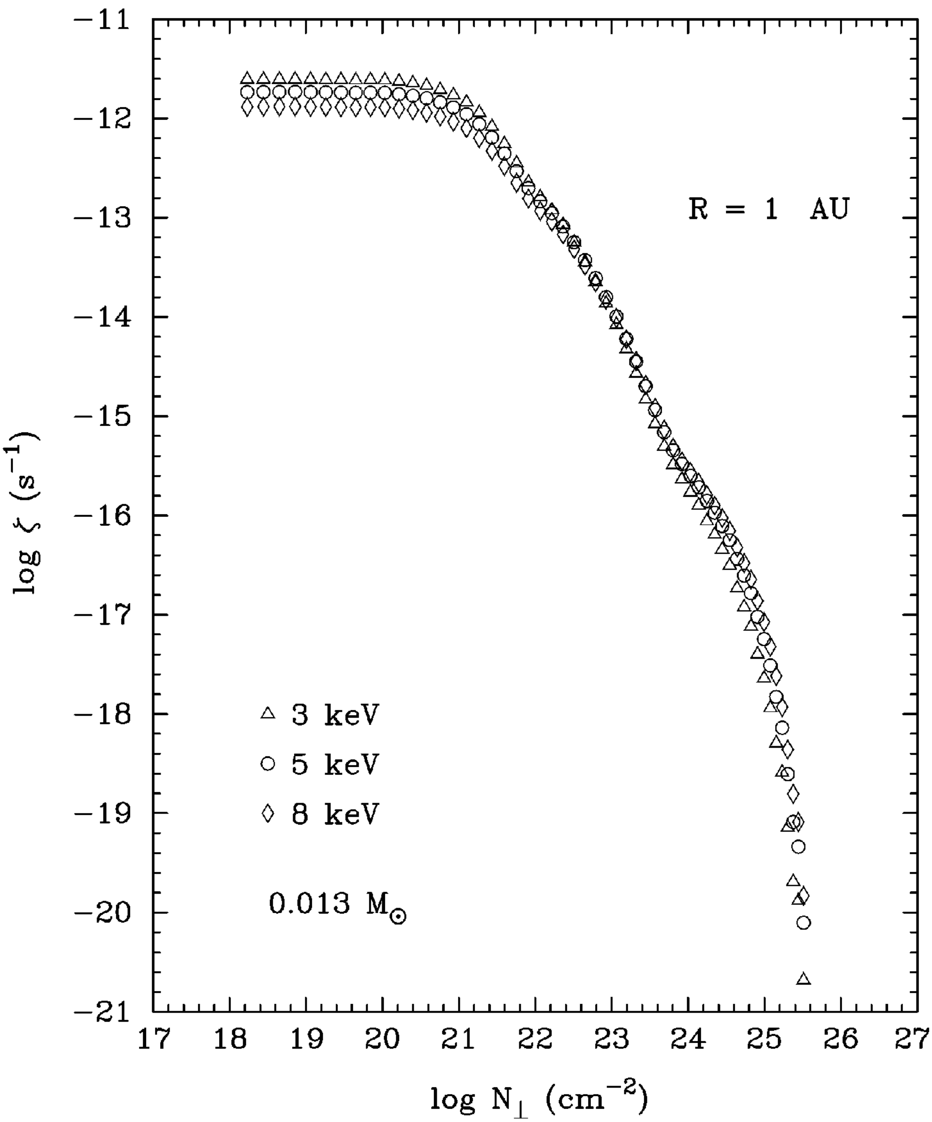


Figure 8 X-ray ionization of a circumstellar disk for X rays of several energies, calculated at $r = 1$ AU for a solar nebular model (Igea & Glassgold 1999). For comparison, the ionization from galactic cosmic rays is estimated to be $\log \xi \sim -17\ s^{-1}$.

rotational transition of HeH^+, and the [OI] 63-μm, [SII] 35-μm, [FeII] 26-μm, and [CII] 158-μm fine-structure lines (Maloney et al 1996). Such lines are being sought with the ISO satellite.

A dust particle subject to an X-ray will absorb most of the secondary electrons, resulting in increased temperature. For example, a small grain with $a = 5$ nm, absorbs all photons with energy $E_x < 0.1$ keV, whereas a large grain with $a = 200$ nm absorbs all photons with $E_x < 2$ keV (Dwek & Smith 1996). Very small grains may evaporate completely, which suggests that their unidentified infrared emission features in the 3- to 13-μm band may disappear near X-ray luminous YSOs (Voit 1992). This effect may have been seen in active galactic nuclei, in which ISO spectra show the disappearance of the near-infrared PAH features (Genzel et al 1998).

Laboratory accelerator X-ray exposures of various materials relevant to interstellar grains (carbonaceous compounds, silicates, etc) have recently been conducted to study the structural damage produced by X-irradiation (Gougeon 1998). Radiation doses equivalent to those obtained at 0.1 pc from a TTS having an L_X of approximately 10^{30} erg s^{-1} for a period of 10^8 years cause dehydrogenation and breakage of aromatic rings in hydrocarbons but have little effect on silicates. X-irradiation will also cause photodissociation and chemical changes in the ices of dust grain mantles (Cornelison et al 1998). These possible effects of YSO X rays on dust mainly affect line profiles, and their detection must await high-resolution spectroscopic study with future instruments, such as those planned for the SIRTF satellite.

5.3 Meteorite Exposure to Energetic Particles and Shocks

In addition to the readily observed X rays from kilo electron volt plasmas and radio-band gyrosynchrotron radiation from MeV electrons produced by magnetic reconnection events in YSOs, it is reasonable to suppose that, as in solar flares, these events are accompanied by the release of MeV nuclei and strong shocks that propagate into the circumstellar matter. Although no direct astronomical evidence for the bombardment of disk material by protons and shock can be inferred from studies of YSOs, considerable evidence for such processes in the early solar nebula has been found in the meteoritic record.

Meteorites are typically small bodies from the asteroid belt whose orbits are perturbed to collide with Earth; they survive passage through the Earth's atmosphere and are retrieved for study. They give a unique—but incomplete and complex—view of solid materials throughout the early phases of solar evolution (Kerridge & Matthews 1989). Whereas many meteorites show evidence of extensive processing (elemental differentiation, impact shocks, aqueous chemistry, etc), carbonaceous chondrites and portions of other types appear to be relatively pristine remnants of the pre–main-sequence solar nebula. Carbonaceous chondrites are relatively loose conglomerates of early materials, including spheroidal lumps of melted rock (chondrules), rare melted Ca-Al–rich inclusions (CAIs), coal-like carbonaceous matrix, and trace fractions of organic molecules (such as amino acids) and presolar (interstellar) carbonaceous grains. Radioactive dating indicates they were formed

4.55 to 4.56 Gyr ago and are thus contemporaneous within approximately 10 Myr (Russell & Wadhwa 1999).

Four avenues of meteoritic research relate to the magnetic activity and associated high-energy processes discussed in the astronomical contexts above. In some cases, the meteoritic evidence and astronomical evidence clearly support each other, while in others the relationship is only one of several possible interpretations of the meteoritic evidence.

Chondrule Formation The majority of meteorites are composed largely of chondrules, round millimeter-size igneous rocks. Laboratory investigations have established that they were flash-melted to temperatures of approximately 2000 K, followed by slow cooling over hours. The chondrule precursors are probably loose balls of interstellar dust that coagulated in the disk. The exact cause of the melting has been an enigma for more than a century, and many models have been proposed (see reviews by Wasson 1993 and Boss 1996). Such models include melting in accretion shocks caused by inhomogeneous infall onto the circumstellar disk, impact shocks from planetisimal collisions, bow shocks when planetisimals acquire supersonic velocities caused by resonances with Jupiter, ablation when planetisimals enter planetary atmospheres, FU Orionis outbursts, lightning caused by charge separation in the disk, and magnetic-reconnection flares. Melting by nebular shock waves successfully explains chondrule petrologic properties, but it is unclear whether these shocks are produced by solid-body kinetics within the solar nebula or from external agents such as magnetic flaring (Connolly & Love 1998).

The astronomical findings discussed here clearly support a model of chondrule melting by flare shocks. Several variants of this idea have been discussed. Levy & Araki (1989) propose that the YSO disk continually generates magnetic fields, which erupt into the disk corona, are pulled and twisted by disk Keplerian motions, reconnect, and produce shocks. Magnetic-field amplification by an α-ω dynamo or Balbus-Hawley instability in the differentially rotating disk supports the concept of an MHD disk that continuously creates and reconnects fields (Section 4). Cameron (1995) proposes that ordinary chondrules were melted during the WTT/Class III phase by magnetic reconnection flares produced in a bow shock between a stellar wind and a truncated disk. Shu et al (1997) propose that dust balls are lifted from the disk by the outflowing wind and are melted by reconnection flares around the complex star-disk magnetic interface, and the resulting chondrules are cast outward to orbit further out in the disk.

Natural Remanent Magnetism Polarization analysis of a wide variety of chondrules indicates that they were formed in the presence of a strong $\sim$1-G magnetic field (Levy 1978; review by Saguira & Strangway 1988). Field orientations differ between chondrules in a meteorite, indicating that the field was embedded during chondrule melting and cooling—not during later consolidation or processing. Because the location of chondrule melting in the YSO system is not certain, it is not clear whether this natural-remanent magnetism was caused by stellar fields around the disk corotation radius, interstellar cloud fields that had not been fully extruded from the disk, or fields amplified within the disk. The ubiquity of magnetism in many types of meteorites and the strength of the implied field seem to support the generation of fields throughout the disk.

^{21}Ne and Particle-Track Excesses in Meteoritic Grains For some grains in carbonaceous chondrites, the exposure to energetic particles has two manifestations: excesses of spallogenic ^{21}Ne and high densities of particle tracks from heavy nuclei (reviews by Woolum & Hohenberg 1993, Rao et al 1997). Surrounding grains do not show these effects, indicating they arose when the grains were freely floating in the solar nebula before incorporation into the meteorite. Detailed arguments convincingly demonstrate that irradiation is caused by an active early Sun, with energetic particle fluxes elevated at least a factor of ten above contemporary levels, and cannot be caused by long-duration exposure to galactic cosmic rays. This case is perhaps the clearest in which meteorites show direct effects of the flaring activity seen in YSOs by X-ray and radio telescopes.

Short-Lived Isotopic Anomalies in Ca-Al–Rich Inclusions CAIs exhibit very puzzling isotopic anomalies, including excess short-lived nuclides such as ^{41}Ca and ^{26}Al with radioactive half-lifetimes of 0.15 Myr and 1.1 Myr, respectively (review Goswami & Vanhala 1999). This finding indicates that either the young solar system produced these nuclei in situ by nuclear spallation, or that the solar nebula was contaminated with freshly synthesized nuclear products from stellar sources immediately before the formation of certain inclusions and chondrules. Virtually all simple models for isotopic anomalies encounter difficulties. For example, external seeding by a Type-II supernova could account for the ^{41}Ca, but it produces too much ^{60}Fe, and its distance must be tuned to avoid disrupting the molecular cloud core that collapsed to form the solar system. An asymptotic giant branch red giant star during dredge-up phase passing through the molecular cloud could account for the ^{41}Ca and ^{26}Al but not the observed ^{53}Mn.

The high levels of magnetic activity found in YSOs support models in which at least some meteoritic isotopic anomalies are produced within the YSO system by MeV particle spallation of meteoritic material. This idea has a long heritage (e.g. Fowler et al 1962, Clayton et al 1977, Lee 1978, Feigelson 1982, Levy & Araki 1989, Lee et al 1998) but has generally not gained wide acceptance. In the most thorough analysis to date, Lee et al (1998) calculate that the ^{41}Ca anomaly can arise from reactions such as ^{42}Ca(p, pn) ^{41}Ca and ^{40}Ca$(\alpha, {}^{3}$He$)$ ^{41}Ca, in which the protons and alpha particles are accelerated in YSO flares. The high abundance of ^{26}Al is attributed to irradiation by ^{3}He-rich events as seen in solar impulsive flares, giving reactions such as ^{24}Mg$(^{3}$He$, p)$ ^{26}Al. Overproduction of ^{41}Ca is avoided by particle absorption in thick rims. These ideas have the advantage of residing within the comprehensive x-wind model, which also explains YSO magnetic activity, accretion, winds and Herbig-Haro jets, chondrule melting, and dispersal (Shu et al 1997). However, spallation models fail to produce sufficient ^{60}Fe and may overproduce other isotopes.

5.4 Shock Effects in the Interstellar Medium

Other high-energy processes linked with YSOs may also affect the dense interstellar medium beyond the immediate YSO environment, owing to shocks from energetic outflows and winds. The nonthermal radio emission of the outflows of T Tauri South and the Serpens triple source indicates that electron acceleration can be efficient in YSO jets (Section 3.5). Diffusive shock acceleration can also accelerate protons and heavier particles. Such effects from many mass-losing YSOs might produce excesses of low-energy cosmic rays in a molecular cloud complex, producing spallation reactions near the energy threshold and resulting in diffuse nuclear gamma-ray and X-ray emission lines with identifiable spectral properties (Ip 1995, Tatischeff et al 1998).

6. MAGNETIC ACTIVITY AS A TRACER OF YSO POPULATIONS

In addition to opening a new window into YSO astrophysics, astronomical surveys of magnetically active YSOs can serve as a powerful tool for finding previously missed YSOs and studying their collective properties. An unbiased census of YSO populations from different star-forming clouds is essential in addressing a variety of important issues concerning star formation and pre–main-sequence evolution. Does a molecular cloud form stars continuously over 10^7 years, in several episodes, or in a brief terminal starburst? Is the star formation efficiency of a cloud, $M_{\rm stars}/M_{\rm gas}$, low (perhaps five percent) or high (50 percent) over its lifetime? What is the distribution of longevities of circumstellar disks, and what does this distribution imply for the time scales available for planet formation? What can be learned about the dynamics of star formation from the kinematics of YSOs?

X-ray surveys are particularly effective for locating Class III WTT stars in crowded stellar fields around nearby star-forming regions. Such stars are largely missed by infrared surveys, because their cool blackbody spectral energy distributions cannot be distinguished from those of main-sequence stars. Before X-ray surveys, YSO samples were dominated by Class 0–II stars with ages less than or equal to two Myr, owing to their strong infrared and Hα excesses. Yet, because they last longer than earlier evolutionary phases, Class III stars must outnumber all other YSOs when averaged over all current and past star-forming regions. Thus, a large population of older WTT stars and post-T Tauri stars must exist (Herbig 1978, Feigelson 1996). The characteristics that most readily distinguish older YSOs from ordinary main-sequence stars are high $L_{\rm x}/L_{\rm bol}$ (Section 3) and high-surface lithium abundance revealed through the Li 670.7-nm absorption line

(Martín 1997). Because the YSO X-ray luminosity function is relatively unchanged along the Hayashi tracks from less than 1 to $\simeq$ 50 Myr, X-ray surveys locate considerable numbers of both older WTT stars and previously unrecognized young WTT stars, which are coeval with the more prominent CTT stars. One major problem is that, as older YSOs stars are considered, one must examine ever larger regions around star-forming clouds because of their kinematic dispersion. Efforts to address the astrophysical questions above should thus be viewed with caution, as the YSO samples—even after enhancement by X-ray surveys—are still spatially incomplete and flux limited.

6.1 Census of YSOs Within Star-Forming Regions

The most reliable census of X-ray–emitting T Tauri stars comes from a few deep ROSAT images of nearby active star-forming clouds, in which the newly discovered X-ray–emitting stars have been characterized spectroscopically and photometrically and placed on the Hertzsprung-Russell diagram. These stars include L1495W in Taurus-Auriga (Strom & Strom 1994), Chamaeleon I (Figure 9; Feigelson et al 1993, Lawson et al 1996), and IC348 in Perseus (Preibisch et al 1996, Herbig 1998). These X-ray surveys, combined with previous optical-infrared YSO surveys, show that Class III stars outnumber Class II stars within active star-forming regions at least by factors of 2–3:1. It is surprising that, in the Chamaeleon I and Taurus-Auriga clouds, the age distribution of the Class III stars is substantially identical to the Class II age distribution (Figure 9).

The large population of X-ray–discovered Class III stars has two immediate consequences. First, the star formation rate of a cloud, measured in stars/Myr, is higher than that inferred from early samples dominated by emission line Class II stars. The inferred star formation efficiency is probably more than doubled, but this quantity is more difficult to measure, as older Class III stars may have drifted far from the cloud and could be missing from the census. Also, molecular material is likely to decrease over time because of star formation and cloud disruption or evaporation. Nonetheless, it is likely that star-forming clouds that were once thought to have star formation efficiencies of approximately ten percent (Cohen & Kuhi 1979) may actually have efficiencies of approximately 20 to 30 percent.

Second, the presence of many Class III stars near the stellar birth line implies that, at least in Chamaeleon I, about half of low-mass stars cease interacting with their circumstellar disks (and usually lose any detectable disk) within one Myr. Millimeter studies of CTT and WTT populations also indicate that early disk dissipation is common and can occur over timescales of 10^5 years or less (André & Montmerle 1994). Earlier estimates that disks dissipate on timescales of two to three Myr based on less complete Einstein Observatory data (Strom et al 1989) are probably not reliable. Indeed, it is not clear that there is any preferred disk lifetime, because Class II and III stars coexist along most of the Hayashi track. Rather, the data suggest the distribution of disk longevities ranges smoothly from 10^5 to $\simeq 2 \times 10^7$ years (Lawson et al 1996). This result may be an important

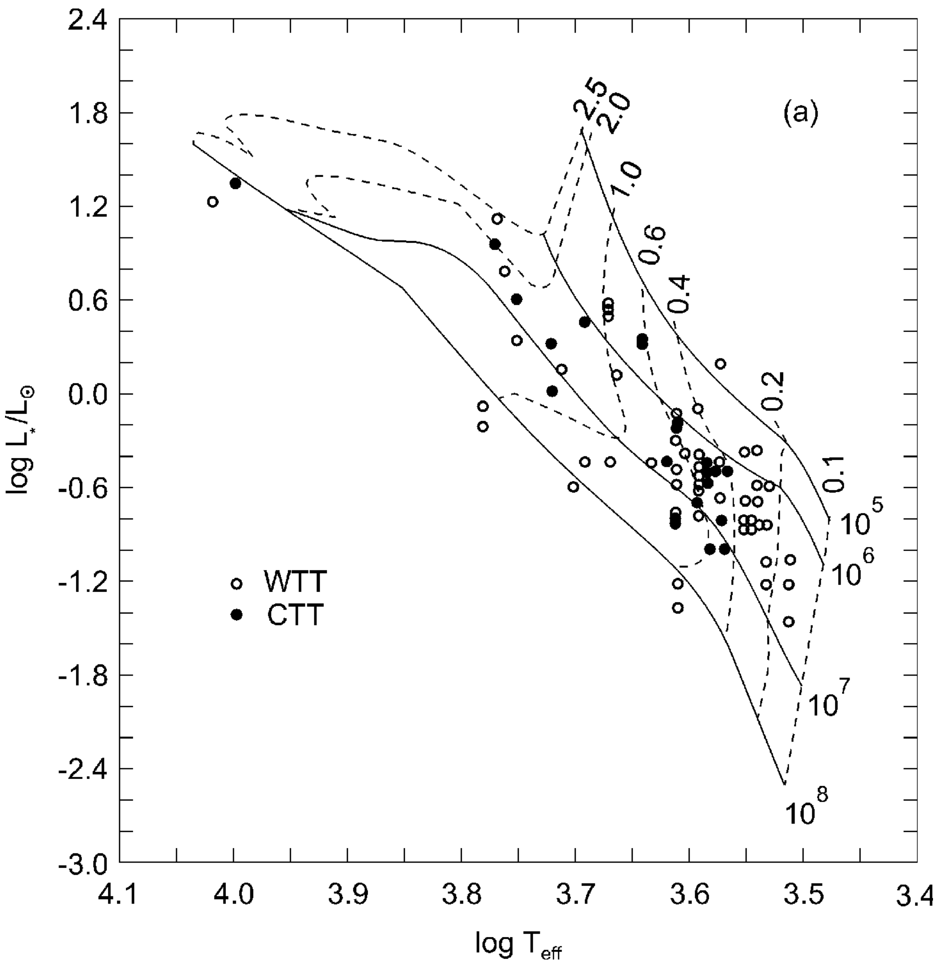


Figure 9 Hertzsprung-Russell diagram of 80 well-characterized YSOs in the Chamaeleon I star-forming cloud. *Filled circles* are CTTs, *open circles* are WTTs, and *dotted lines* are theoretical evolutionary tracks labeled by mass (in $M_{\odot}$) and by age (in yrs). (Adapted from Lawson et al 1996.)

input into models of planet formation in the solar nebula and other circumstellar disks. This empirical evidence for a wide range of disk lifetimes agrees nicely with theoretical analyses indicating that star-disk coupling can efficiently transfer momentum from the star so that a broad distribution of disk lifetimes explains the wide dispersion of rotational velocities among T Tauri stars and open cluster stars (Bouvier et al 1997).

An early unbiased survey of lithium-rich stars in a young stellar cluster suggests that X-ray–selected samples are reasonably complete for intermediate-mass stars ten Myr old or younger (Preibisch et al 1998b). If the census of all YSOs from a given cloud is complete, then the cloud's star formation history can be established by counting stars vertically along the Hayashi tracks. One such analysis in the Ophiuchus cloud complex suggests that star formation starts slowly and accelerates towards a terminal starburst (Martín et al 1999), as may be expected if ambipolar diffusion delays gravitational collapse (Palla & Galli 1997). However, the distribution of stellar ages in the Chamaeleon I cloud suggests a more continuous star formation history (Lawson et al 1996).

6.2 Census of Dispersed YSOs

These efforts to develop complete YSO samples are compromised by the likelihood that many of the older WTT and post-T Tauri stars have kinematically dispersed from the cloud vicinity (Feigelson 1996). Unless corrections for dispersion are made, all existing T Tauri samples, even with X-ray–discovered Class III stars, show a steep decline in star formation rates for stars older than 2 Myr. Stars inheriting velocities of $\sim$1 km s^{-1}, which is the characteristic velocity dispersion within molecular clouds on small scales, produce populations that disperse more than 10 to 20 degrees if star formation continues for ten Myr in nearby star formation regions ($d \simeq 150$ pc).

This hypothesis is supported by the discoveries of what appear to be many Class III stars at large distances from active star-forming clouds (Figure 10). The ROSAT All-Sky Survey (RASS) has revealed thousands of X-ray sources associated with 9- to 15-magnitude stars at low galactic latitudes, many of which are late-type stars with strong Li 670.7 nm lines (0.01 to 0.05 nm equivalent widths) characteristic of WTT stars (e.g. Neuhäuser et al 1995a, Alcalá et al 1995, Sterzik et al 1995, Wichmann et al 1996). A vigorous debate has grown over these findings. Some argued that the stars are 50- to 100-Myr-old ZAMS and not 1- to 30-Myr-old stars on the Hayashi tracks (Briceño 1997, Favata et al 1997). Many recent studies are extending the survey to the entire celestial sphere and measuring various properties of these stars.

X-ray surveys have also uncovered a previously unrecognized nearby pre-main sequence star cluster, the eta Cha cluster (Mamajek et al 1999), and have located new members of the TW Hya association (Webb et al 1999). These are very nearby ($d = 50 - 100$ pc) open clusters about 10 Myr old, lying far from significant molecular material and exhibiting high proper motions. They are distinctly different in one respect: TW Hya stars are spread over a 30-degree (30 pc) region, while the known eta Cha members lie within a 0.5 degree (1 pc) region. Both the eta Cha cluster and RASS stars spread throughout the Chamaeleon region have proper motion similar to that of the Sco-Cen association. It thus seems possible that the Sco-Cen star-forming region extends tens of parsecs further into the southern sky than previously thought.

Although our understanding of these widely dispersed magnetically active Li-rich young stars is still incomplete, some results are emerging. Observationally,

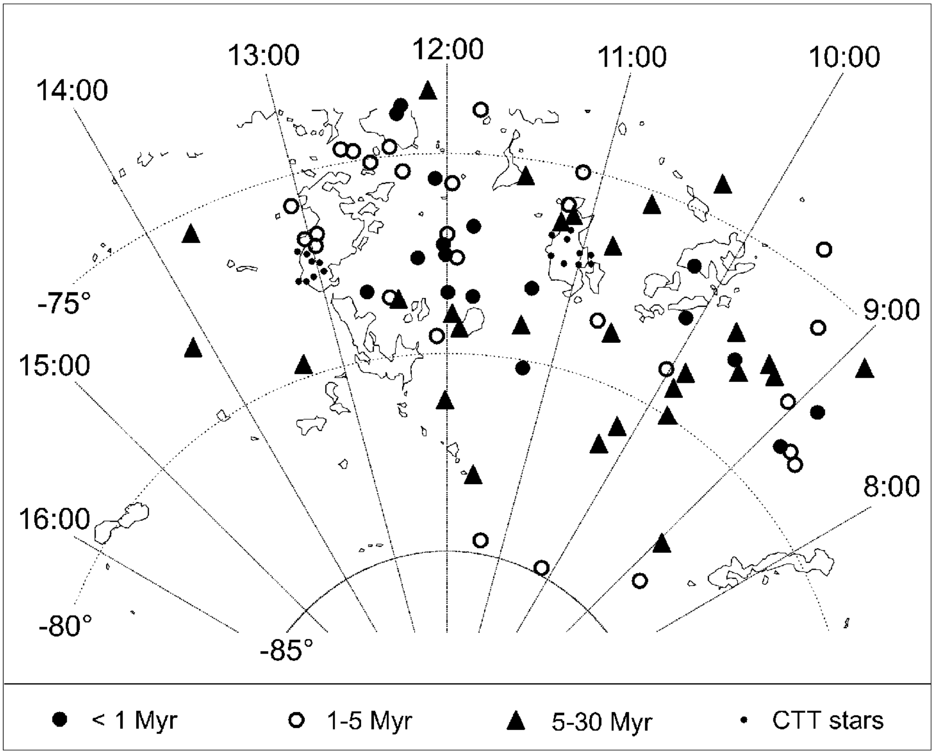


Figure 10 Spatial distribution of Li-rich magnetically active stars that appear to be Class III YSOs, found in the ROSAT All-Sky Survey around the Chamaeleon star-forming clouds. Contours indicate small molecular clouds, and small dots represent previously known Class II stars. (Adapted from Neuhäuser 1997.)

several recent studies indicate that the RASS stars are a mixture of older ZAMS stars and younger but widely dispersed WTT stars, in which the ratio between the types varies across the sky (Martín 1997, Covino et al 1997, Motch et al 1997, Alcalá et al 1998). These studies, however, depend on the subtle discrimination of WTT, post-T Tauri, and ZAMS stars from their location on the T_{eff}-lithium equivalent-width diagram. A cross-correlation between the Tycho parallax and RASS X-ray catalogs produced a sample of approximately 9000 stars, showing that a considerable fraction of the RASS stars appear to be distributed in a disk associated with Gould's Belt (Guillout et al 1998), a well-known ring of star-forming clouds, OB associations, and open clusters lying between 150 and 500 pc from the Sun. As the RASS is severely flux limited, detecting only 20 percent of the youthful stellar population at $d \simeq 150$ pc, tens of thousands of low-mass stars may be dispersed throughout Gould's Belt.

Astrophysically, several possible origins of isolated WTT stars lying far from a star-forming cloud are viable. First, they may be dynamically ejected at high velocity from star-forming regions caused by gravitational scattering from close binaries (Sterzik & Durisen 1995). Although energetically feasible, the efficiency of ejection would have to be implausibly high to explain the large observed population of dispersed WTT stars. Second, stars may inherit high velocities from cloudlets within giant molecular clouds (Feigelson 1996). Molecular spectroscopy shows that cloud complexes typically exhibit supersonic turbulence with large-scale velocity dispersions on the order of ten km s^{-1}, which is sufficient to project stars tens of parsecs while still on the Hayashi tracks. However, the highest-velocity cloudlets are typically not associated with the densest star-forming cloud cores. Third, a starburst may occur near the end of molecular cloud lifetimes (perhaps star formation is delayed by ambipolar diffusion), so that the molecular material dissipates soon after star formation resulting in groups of isolated WTT stars (Palla & Galli 1997).

However incomplete the current samples are, X-ray surveys are leading to a resolution of the long-standing mystery of the missing post-T Tauri stars (Herbig 1978) and are simultaneously uncovering a widely distributed population of low-mass young stars associated with Gould's Belt and/or the Local Association (Eggen 1999). As the properties of the dispersed magnetically active young stars are elucidated, significant insights into the history and dynamics of star formation in the solar neighborhood over the past 10^8 years may emerge.

7. CONCLUDING REMARKS

A confluence of astronomical techniques—imaging X-ray astronomy, polarization-sensitive radio interferometry, highly accurate optical spectroscopy and photometry, and laboratory analysis of meteoritic materials—persuasively show that high-energy processes are prevalent in low-mass YSOs. The rapid heating and cooling of plasma to 10^7 to 10^8 K and acceleration of particles to MeV energies are almost certainly not the product of hydrodynamical phenomena such as gravitational collapse and accretion. These violent phenomena must arise from efficient MHD processes such as solar-type magnetic reconnection flares. The X-ray manifestation of this enhanced magnetic activity is a ubiquitous characteristic of low-mass YSOs, present from the Class I protostellar phase with ages of approximately 10^5 years to stars approaching the ZAMS with ages of 10^7 years. X-ray tracers of YSOs have led to substantial increases in YSO samples, which in turn provide new insights into the history of star formation in the solar neighborhood.

These findings show that the traditional hydrodynamic paradigm for understanding the earliest stages of stellar evolution is not complete. The most important astrophysical effect may be the ionization produced by flare X rays, which, unlike the HII regions of early-type stars, produces extended regions of partially ionized molecular gas. If X-ray emission begins in the earliest Class 0 phase, then YSO ionization may crucially affect the gravitational collapse of star formation. It is not clear today whether this occurs, because there is only one tentative X-ray detection of a Class 0–I YSO (CrA IRS7). Because X-ray emission is definitely prevalent in the Class I–II phases, X-ray ionization is quite likely to play a central role in the astrophysics and evolution of the circumstellar disk. One important effect is the induction of MHD turbulence and viscosity, thereby regulating accretion onto the star. X-ray ionization may also be necessary for the magnetic coupling of the central star to the inner disk, and coupling of the disk to magnetically accelerated and collimated outflows.

The energetic photons and particles produced in YSO flares may furthermore account for long-standing findings in meteorites that are quite difficult to explain in the quiet hydrodynamic model of the solar nebula. MeV protons, presumed to accompany the MeV electrons detected in YSO gyrosynchrotron radio flares, may account for excess particle tracks and spallogenic isotopes in meteorites. Flare shocks may melt chondrules.

In the near future, empirical investigations of hot energetic processes in cold YSOs are likely to thrive. The Chandra X-ray Observatory and the X-ray Multimirror Mission, to be launched soon, represent a considerable improvement in X-ray observational capability, particularly in the harder bands that are much less attenuated by foreground material. A number of problems raised in this review may be solved with these new observatories. For example, Chandra, with its subarcsecond resolution, will be able to detect thousands of T Tauri stars in the Orion giant molecular cloud. Combined with optical studies placing the stars on the Hertzsprung-Russell diagram (Hillenbrand 1997), one can disentangle L_x-mass and L_x-age correlations to study the causes of YSO magnetic activity (see Section 3.2). The excellent high throughput of XMM will allow the detection of very faint and low-mass YSOs deeply embedded in molecular cores, including young brown dwarfs, and will provide direct measurements of extinction needed to obtain accurate X-ray luminosities. The search for X rays from Class 0 protostars has particularly important astrophysical implications, such as deciding whether infall is braked by the onset of YSO-ionizing radiation or whether Class 0 outflows have a gravitational or magnetic origin.

Proposed radio astronomical facilities like the Atacama Large Millimeter Array, Very Large Array upgrade, and Square Kilometer Array would significantly boost the study of MeV particles in YSOs, because YSO fluxes are close to the sensitivity limits of current telescopes. Insight should emerge on the magnetic structures, disk gas chemistry, and dust properties in magnetically active YSOs. The proliferation of 8-m–class optical/infrared telescopes, with techniques such as Doppler imaging and high-resolution IR spectroscopy and interferometry, as well as planned infrared space missions such as SIRTF and NGST, will permit more accurate characterization of the magnetic properties of the central stars and the accretion process in YSO systems.

There are urgent needs for more theoretical and laboratory development of the issues discussed here. The concept of a magnetically active but thermodynamically cold molecular disk linked to other structures within YSO systems must be investigated in greater detail. This is a challenging problem requiring time-dependent, three-dimensional MHD calculations with reconnection, ionization and heating.

The effects of X rays on circumstellar gas and disks, which so far have been studied primarily for disks, should be extended to protostellar envelopes. These efforts are closely related to the study of high-energy effects on cold material around active galactic nuclei. There has also been inadequate study of the effects of flare shocks and energetic particles on solids. Further accelerator experiments with X rays and particles should be pursued actively. The final evaluation of the astrophysical importance of energetic processes in YSOs awaits these future investigations.

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LITERATURE CITED

Agrawal PC, Koyama K, Matsuoka M, Tanaka Y. 1986. *PASJ* 38:723–79

Aikawa Y, Umebayashi T, Nakano T, Miyama S. 1998. *Faraday Discuss.* 109:281–301

Alcalá JM, Chavarria-KC, Terranegra L. 1998. *Astron. Astrophys.* 330:1017–28

Alcalá JM, Krautter J, Schmitt JHMM, Covino E, Wichmann R, Mundt R. 1995. *Astron. Astrophys. Suppl.* 114:109–34

Alcalá JM, Terranegra L, Wichmann R, Chavarriá-KC, Krautter J, et al. 1996. *Astron. Astrophys. Suppl.* 119:7–24

Alcalá JM, Krautter J, Covino E, Neuhäuser R, Schmitt JHMM, Wichmann R. 1997. *Astron. Astrophys.* 319:184–200

Alcalá JM, Chavarria–KC, Terranegra L. 1998. *Astron. Astrophys.* 330:1017–28

Ambartsumian VA, Mirzoyan LY. 1982. *Astrophys. Sp. Sci.* 84:317–30

André P. 1987. In *Protostars and Molecular Clouds*, eds. T. Montmerle, C. Bertout, 143–87, Saclay, France: CEA

André P, Montmerle T, Feigelson ED. 1987. *Astron. J.* 93:1182–98

André P, Deeney BD, Phillips RB, Lestrade J-F. 1992. *Astrophys. J.* 401:667–77

André P, Montmerle T. 1994. *Astrophys. J.* 420:837–62

André P. 1996. In *Radio Emission from the Stars and the Sun*, ed. AR Taylor, JM Paredes, Vol. 93, pp. 273–84. San Francisco: ASP

Anglada G. 1996. In *Radio Emission from the Stars and the Sun*, ed. AR Taylor and JM Paredes, Vol. 93, pp. 3–14. San Francisco: ASP

Armitage PJ, Clarke CJ. 1996. *MNRAS* 280:458–68

Bachiller R. 1996. *Annu. Rev. Astron. Astrophys.* 34:111–54

Balbus SA, Hawley, JF. 1991. *Astrophys. J.* 376:223–33

Banaskiewicz M, Axford WI, McKenzie JF. 1998. *Astron. Astrophys.* 337:940–94

Becker RH, White RL. 1985. *Astrophys. J.* 297:649–51

Becker RH, White RL. 1988. *Astrophys. J.* 324:893–98

Beckwith SVW, Sargent AI, Chini RS, Guesten R. 1990. *Astron. J.* 99:924–45

Bertout C. 1989. *Annu. Rev. Astron. Astrophys.* 27:351–95

Bertout C, Harder S, Malbet F, Mennessier C, Regev O. 1996. *Astron. J.* 112:2159

Bieging JH, Cohen M. 1989. *Astron. J.* 98:1686–92

Bieging JH, Cohen M, Schwartz PR. 1984. *Astrophys. J.* 282:699–708

Birk GT. 1998. *Astron. Astrophys.* 330:1070–76

Blandford RD, Payne DR. 1982. *MNRAS* 199:883–903

Bontemps S, André P, Terebey S, Cabrit S. 1996. *Astron. Astrophys.* 311:858–72

Boss AP. 1996. In *Chondrules and the Protoplanetary Disk*, eds. RH Hewins, RH Jones, ERD Scott, 257–63, New York: Cambridge Univ. Press

Bouvier J, Appenzeller, I. 1992. *Astron. Astrophys. Suppl.* 92:481–516

Bouvier J, Covino E, Kovo O, Martín EL, Matthews JM, et al. 1995. *Astron. Astrophys.* 299:89–107

Bouvier J, Forestini M, Allain S. 1997. *Astron. Astrophys.* 326:1023–43

Bradt H, Kelley RL. 1979. *Astrophys. J. Lett.* 228:L33

Brandner W, Köhler R. 1998. *Astrophys. J.* 499:L79–82

Briceño C, Hartmann LW, Stauffer JR, Gagné M, Stern RA. 1997. *Astron. J.* 113:740–51

Brown A. 1987. *Astrophys. J.* 322:L31–34

Brown A, Walter FM, Ambruster C, Stewart RT, Jeffries R. 1996. In *Radio Emission from the Stars and the Sun*, ed. AR Taylor, JM Paredes, Vol. 93, pp. 294–296, San Francisco: Astron. Soc. Pacific

Busso M, Gallino R, Wasserburg GJ. 1999. *Annu. Rev. Astron. Astrophys*. 37:239–309

Caillault J-P, Magnani L, Fryer CA. 1995. *Astrophys. J.* 441:261–69

Calvet N, Basri G, Kuhi LV. 1984. *Astrophys. J.* 277:725–37

Calvet N, Gullbring E. 1998. *Astrophys. J.* 509:802–18

Cameron AGW. 1995. *Meteoritics* 30:133–61

Cameron AC, Campbell CG. 1993. *Astron. Astrophys.* 274:309–18

Carkner L, Feigelson ED, Koyama K, Montmerle T, Reid IN. 1996. *Astrophys. J.* 464:286–305

Carkner L, Mamajek E, Feigelson ED, Neuhäuser R, Wichmann R, et al. 1997. *Astrophys. J.* 490:735–43

Carkner L, Kozak JA, Feigelson ED. 1998. *Astron. J.* 116:1933–39

Casanova S, Montmerle T, Feigelson ED, André P. 1995. *Astrophys. J.* 439, 752–70

Chiang E, Phillips RB, Lonsdale CJ. 1996. *Astron. J.* 111:355–64

Churchwell E, Wood DOS, Felli M, Massi M. 1987. *Astrophys. J.* 321:516–29

Ciolek GE, Mouchovias TC. 1995. *Ap. J.* 454:194–216

Clayton DD, Dwek E, Woosley SE. 1977. *Astrophys. J.* 214:300–15

Cohen M, Bieging JH. 1986. *Astron. J.* 92:1396–1402

Cohen M, Kuhi LV. 1979. *Astrophys. J. Suppl.* 41:743–843

Connolly HC Jr., Love SG. 1998. *Science* 280:62–67

Cooke BA, Ricketts MJ, Maccacaro T, Pye JP, Elvis M, et al. 1978. *MNRAS* 182:489

Cornelison DM, Dillingham TR, Tegler SC, Galle K, Miller GA, Lutz BL. 1998. *Astrophys. J.* 505:443–51

Covino E, Alcalá JM, Allain S, Bouvier J, Terranegra L, et al. 1997. *Astron. Astrophys.* 328:187–202

Dalgarno A, McCray RA. 1972. *Annu. Rev. Astron. Astrophys.* 10:375–426

Damiani F, Micela G, Sciortino S, Harnden FR Jr. 1995a. *Astrophys. J.* 446:331–40

Damiani F, Micela G. 1995b. *Astrophys. J.* 446:341–49

DeCampli WM. 1981. *Astrophys. J.* 244:124–46

den Boggende AJF, Mewe R, Gronenschild EHBW, Heise J, Grindlay JE. 1978. *Astron. Astrophys* 62:1–7

Donati J-F, Semel M, Carter BD, Rees DE, Cameron AC. 1997. *MNRAS* 291:658–82

Dulk GA. 1985. *Annu. Rev. Astron. Astrophys.* 23:169–224

Dutrey A, Guilloteau S, Simon M. 1994. *Astron. Astrophys.* 286:149–59

Dwek E, Smith RK. 1996. *Astrophys. J.* 459:686–700

Edwards S, Strom SS, Hartigan P, Strom KM, Hillenbrand LA, et al. 1993. *Astron. J.* 106:372–82

Eggen O. 1999. *Astron. J.* In press

Favata F, Micela G, Sciortino S. 1997. *Astron. Astrophys.* 326:647–54

Favata F, Micela G, Sciortino S. 1998. *Astron. Astrophys.* 337:413–20

Favata F, Micela G, Sciortino S. 1999. *Astron. Astrophys.* In press

Feigelson ED. 1982. *Icarus* 51:155–63

Feigelson ED. 1996. *Astrophys. J.* 468:306–22

Feigelson ED, Carkner L, Wilking BA. 1998. *Astrophys. J. Lett.* 494:L215–18

Feigelson ED, Casanova S, Montmerle T, Guibert JR. 1993. *Astrophys. J.* 416:623–46

Feigelson ED, DeCampli WM. 1981. *Astrophys. J. Lett.* 243:L89–93

Feigelson ED, Giampapa MS, Vrba FJ. 1991. In *The Sun in Time*, ed. CP Sonett, MS Giampapa, MS Matthews, p. 658–81. Tucson, AZ: Univ. Ariz. Press

Feigelson ED, Jackson JM, Mathieu RD, Myers PC, Walter FM. 1987. *Astron. J.* 94:1251–59

Feigelson ED, Kriss, GA. 1981. *Astrophys. J. Lett.* 248:L35–38

Feigelson ED, Kriss GA. 1989. *Astrophys. J.* 338:262–76

Feigelson ED, Lawson WA. 1997. *Astron. J.* 113:2130–33

Feigelson ED, Montmerle T. 1985. *Astrophys. J.* 289:L19–23

Feigelson ED, Welty AD, Imhoff C, Hall JC, Etzel PB, Phillips RB, Lonsdale CJ. 1994. *Astrophys. J.* 432:373–85

Felli M, Churchwell E, Wilson TL, Taylor GB. 1993a. *Astron. Astrophys. Suppl.* 98:137–64

Felli M, Taylor GB, Catarzi M, Churchwell E, Kurtz S. 1993b. *Astron. Astrophys. Suppl.* 101:127–51

Ferreira J, Pelletier G. 1995. *Astron. Astrophys.* 295:807

Field GB, Rogers RD. 1993. *Astrophys. J.* 403:94–109

Finkenzeller U, Basri G. 1987. *Astrophys. J.* 318:832–43

Fleming TA, Gioia IM, Maccacaro T. 1989. *Astrophys. J.* 340:1011–23

Fowler W., Greenstein J, Hoyle F. 1962. *Geophys. J. R. Astron. Soc.* 6:148–200

Frink S, Rëser S, Neuhäuser R, Sterzik MF. 1997. *Astron. Astrophys.* 325:613–22

Gagné M, Caillault J-P. 1994. *Astrophys. J.* 437:361–83

Gagné M, Caillault J-P, Stauffer JR. 1995. *Astrophys. J.* 445:280–313

Gahm GF. 1980. *Astrophys. J. Lett.* 242:L163–66

Gahm GF, Loden KL, Loden K, Gullbring E, Hartstein D. 1995. *Astron. Astrophys.* 301:89–104

Gammie CF. 1996. *Astrophys. J.* 457:355–62

Garay G, Moran JM, Reid MJ. 1987. *Astrophys. J.* 314:535–50

Geier S, Wendker HJ, Wisotzki L. 1995. *Astron. Astrophys.* 299:39–52

Genzel R, Lutz D, Sturm E, Egami E, Kunze D, et al. 1998. *Ap. J.* 498:579–605

Giacconi R, Murray S, Gursky H, Kellogg E, Schreier E, Tananbaum H. 1972. *Astrophys. J.* 178:281–308

Gilman PA. 1983. In *Solar and Stellar Magnetic Fields,* IAU Symp. 102, ed. JO Stenflo, p. 247. Boston: Reidel

Giovannelli F, Vittone AA, Rossi C, Errico L, Bisnovatyi-Kogan GG. 1995. *Astron. Astrophys. Suppl.* 114:341–61

Glassgold AE, Feigelson ED, Montmerle T. 1999. See Mannings et al 1999.

Glassgold AE, Najita J, Igea J. 1997. *Astrophys. J.* 480:344–50 (Erratum *Astrophys. J.* 485:920)

Goodson AP, Winglee RM, Böhm K-H. 1997. *Astrophys. J.* 489:199–209

Goswami JN, Vanhala H. 1999. See Mannings, et al. 1999

Gougeon S. 1998. Thèse Doct., Univ. Paris VII

Gregorio-Hetem J, Montmerle T, Casanova

S, Feigelson ED. 1998. *Astron. Astrophys.* 331:193–210

Grosso N, Montmerle T, Feigelson ED, André P, Casanova S, Gregorio-Hetem J. 1997. *Nature* 387:56–58

Güdel M, Guinan EF, Skinner SL. 1997. *Astrophys. J.* 483:947–60

Güdel M, Linsky JL, Brown A, Nagase F. 1999. *Astrophys. J.* 511:405–21

Guenther EW, Emerson JP. 1997. *Astron. Astrophys.* 321:803–10

Guenther EW, Lehmann H, Emerson JP, Staude J. 1999. *Astron. Astrophys.* 341:768–83

Guillout P, Sterzik MF, Schmitt JHMM, Motch C, Neuhäuser R. 1998. *Astron. Astrophys.* 337:113–24

Gullbring E, Barwig H, Chen PS, Gahm GF, Bao MX. 1996. *Astron. Astrophys.* 307:791–802

Gullbring E, Barwig H, Schmitt JHMM. 1997. *Astron. Astrophys.* 324:155

Halpern JP, Grindlay JE. 1980. *Astrophys. J.* 242:1041–55

Haro G, Chavira E. 1966. *Vistas in Astronomy,* 8:89–107

Hartmann L. 1998. *Accretion Processes in Star Formation,* Cambridge, UK: Cambridge Univ. Press

Hartmann L, Hewett R, Calvet N. 1994. *Astrophys. J.* 426:669

Hartmann L, Kenyon S, Hartigan P. 1993. In Levy & Lunine 1993, pp. 497–518

Hartmann LW, Soderblom DR, Stauffer JR. 1987. *Astron. J.* 93:907–12

Hatzes AP. 1995. *Astrophys. J.* 451:784

Hayashi C. 1966. *Annu. Rev. Astron. Astrophys.* 4:171–92.

Hayashi M, Shibata K, Matsumoto R. 1996. *Astrophys. J. Lett.* 468:L37–40

Henriksen RN, Mirabel IF, Ptuskin VS. 1991. *Astron. Astrophys.* 248:221–26

Henriksen R, André P, Bontemps S. 1997. *Astron. Astrophys.* 323:549–65

Henry GW, Hall DS. 1994. *Astrophys. J. Lett.* 425:L25

Herbig G. 1962. *Adv. Astron. Astrophys.* 1:47

Herbig GH. 1973. *Astrophys. J.* 182:129

Herbig GH. 1978. In *Problems of Physics and Evolution of the Universe,* ed. LV Mirozyan, pp. 171–79, Yerevan: Acad. Sci. Armenian SSR

Herbig GH. 1998. *Astrophys. J.* 497:736–58

Herbig GH, Soderblom DR. 1980. *Astrophys. J.* 242:628–37

Herbst W. 1989. *Astron. J.* 89:2268–74

Hillenbrand LA. 1997. *Astron. J.* 113:1733–68

Hirose S, Uchida Y, Shibata K, Matsumoto R. 1997. *Pub. Astron. Soc. Japan* 49:193–205

Hoff W, Henning T, Pfau W. 1998. *Astron. Astrophys.* 336:242–50

Igea J, Glassgold AE. 1999. *Astrophys. J.* In press

Ip W-H. 1995. *Astron. Astrophys.* 300:283–88

Jeffries RD, Buckley DAH, James DJ, Stauffer JR. 1996. *MNRAS* 281:100–15

Jensen ELN, Cohen DH, Neuhäuser R. 1998. *Astron. J.* 116:414–23

Johns-Krull CM, Hatzes AP. 1997. *Astrophys. J.* 487:896–915

Johns-Krull CM, Valenti JA, Hatzes AP, Kanaan A. 1999. *Astrophys. J.* 510:L41–44

Joncour I, Bertout C, Ménard F. 1994. *Astron. Astrophys.* 285:L25–28

Joy AH. 1945. *Astrophys. J.* 102:168–95

Kaastra JS, Mewe R. 1993. *Astron. Astrophys. Suppl.* 97:443–82

Kamata Y, Koyama K, Tsuboi Y, Yamauchi S. 1997. *PASJ* 49:461–70

Kastner JH, Zuckerman B, Weintraub DA, Forveille T. 1997. *Science* 277:67–71

Kerridge J, Matthews M., eds. 1989. *Meteorites and the Early Solar System,* Tucson: Univ. Ariz. Press

Köhler R, Leinert C. 1998. *Astron. Astrophys.* 331:977–98

Königl A. 1991. *Astrophys. J.* 370:L39–43

Königl A, Ruden SP. 1993. In Levy & Lunine 1993, 641–87

Koyama K. 1987. *PASJ* 39:245–52

Koyama K, Asaoka I, Kuriyama T, Tawara Y. 1992. *PASJ* 44:L255–57

Koyama K, Hamaguchi K, Ueno S, Kobayashi N, Feigelson ED. 1996. *PASJ* 48:L87–92

Koyama K, Maeda Y, Ozaki M, Ueno S,

Kamata Y, Tawara Y, Skinner S, Yamauchi S. 1994. *PASJ* 46:L125–29

Krautter J, Wichmann R, Schmitt JHMM, Alcalá JM, Neuhäuser R, Terranegra L. 1997. *Astron. Astrophys. Suppl.* 123:329–52

Krolik JH, Kallman TR. 1983. *Astrophys. J.* 267:610–24

Ku WH-M, Chanan GA. 1979. *Astrophys. J. Lett.* 234:L59–63

Kudoh T, Shibata K. 1997. *Astrophys. J.* 476:632–48

Kuhi LV. 1964. *Astrophys. J.* 140:1409–33

Kutner ML, Rydgren AE, Vrba FJ. 1986. *Astron. J.* 92:895–97

Lada CJ. 1987. In *Star Forming Regions*, IAU Symp. 115, eds. M Peimbert, J. Jugaku. Dordrecht: Kluwer

Lada CJ, Kylafis ND. 1991. In *The Physics of Star Formation and Early Stellar Evolution*. Dordrecht: Kluwer

Lamzin SA, Bisnovatyi-Kogan GS, Errico L, Giovannelli F, Katysheva NA, Rossi C, Vittone AA. 1996. *Astron. Astrophys.* 306:877–91

Lawson WA, Feigelson ED, Huenemoerder DP. 1996. *MNRAS* 280:1071–88

Lee T. 1978. *Astrophys. J.* 224:217–26

Lee T, Shu FH, Shang H, Glassgold AE, Rehm KE. 1998. *Astrophys. J.* 506:898–912

Leous JA, Feigelson ED, André P, Montmerle T. 1991. *Astrophys. J.* 379:683–88

Lepp S. 1992. In *Astrochemistry of Cosmic Phenomena*, ed. P. Singh, p. 471–75. Dordrecht: Reidel

Lepp S, Dalgarno A. 1996. *Astron. Astrophys.* 306:L21–24

Lepp S, McCray R. 1983. *Astrophys. J.* 269:560–67

Levy EH. 1978. *Nature* 276:481

Levy EH, Ruzmaikin AA, Ruzmaikina TV. 1991. In *The Sun in Time*, eds. CP Sonnett, MS Giampapa, MS Matthews, pp. 589–632. Tucson: Univ. Arizona Press

Levy EH, Lunine JI eds. 1993. *Protostars and Planets III*, Tucson: Univ. Arizona Press

Levy E, Araki S. 1989. *Icarus* 81:74–91 (and discussion in *Icarus* 87:241–6)

Li J. 1996. *Astrophys. J.* 456:696–707

Luhman KL, Briceño C, Rieke GH, Hartmann L. 1998. *Astrophys. J.* 493:909–13

Magazzù A, Martín EL, Sterzik MF, Neuhäuser R, Covino E, et al. 1997. *Astron. Astrophys. Suppl.* 124:449–67

Magnani L, Caillault J-P, Hearty T, Stauffer J, Schmitt JHMM. 1996. *Astrophys. J.* 465:825–39

Maloney PR, Hollenbach DR, Tielens AG. 1991. *Astrophys. J.* 466:561–84

Mamajek EE, Lawson WA, Feigelson ED. 1999. *Astrophys. J.* 516:L77–80

Mannings V, Boss A, Russell S. eds. 1999. *Protostars and Planets IV*, Tucson, AZ: Univ. Ariz. Press. In press

Mardones D, Myers PC, Tafalla M, Wilner DJ, Bachiller R, Garay G. 1997. *Astrophys. J.* 489:719–33

Markert TH, Winkler PF, Laird FN, Clark GW, Hearn DR, et al. 1979. *Astrophys. J. Suppl.* 39:573

Martín EL. 1997. *Astron. Astrophys.* 321:492–96

Martín EL. 1998. *Astron. J.* 115:351–57

Martín EL, Montmerle T, Gregorio–Hetem J, Casanova S. 1998. *MNRAS* 300:733–46

Mathieu RD, Walter FM, Myers PC. 1989. *Astron. J.* 98:987–1001

Mathieu RD. 1994. *Annu. Rev. Astron. Astrophys.* 32:465–530

McCaughrean MJ, O'Dell CR. 1996. *Astron. J.* 111:1977–86

McKee CF. 1989. *Astrophys. J.* 345:782–801

Micela G, Favata F, Sciortino S. 1997. *Astron. Astrophys.* 326:221

Miller KA, Stone JM. 1998. *Astrophys. J.* 489:890–902

Montmerle T, Koch-Miramond L, Falgarone E, Grindlay JE. 1983. *Astrophys. J.* 269:182–201

Montmerle T, Feigelson ED, Bouvier J, André P. 1993. In Levy & Lunine 1993, 689–717

Montmerle T. 1991. In *The Physics of Star Formation and Early Stellar Evolution*, ed. CJ Lada, ND Kylafis, p. 675. Dordrecht: Kluwer

Motch C, Guillout P, Haberl F, Pakuli M, Piesch W, Reinsch K. 1997. *Astron. Astrophys.* 318:111–133

Mouschovias TC. 1976. *Astrophys. J.* 207:141–58

Mundt R, Walter FM, Feigelson ED, Finkenzeller U, Herbig GH, et al. 1983. *Astrophys. J.* 269:229–38

Nakano M, Yamauchi S, Sugitani K, Ogura K, Kogure T. 1999. *Publ. Astron. Soc. Japan* 51:1–12

Naylor T, Fabian AC. 1999. *MNRAS.* 302:714–22

Neuhäuser R. 1997. *Science* 276:1363–70

Neuhäuser R, Briceño C, Comeron F, Hearty T, Martín E, et al. 1999. *Astron. Astrophys.* 343:883–93

Neuhäuser R, Preibisch T. 1997. *Astron. Astrophys.* 322:L37–40

Neuhäuser R, Sterzik MF, Schmitt JHMM, Wichmann R, Krautter J. 1995a. *Astron. Astrophys.* 295:L5–8

Neuhäuser R, Sterzik MF, Schmitt JHMM, Wichmann R, Krautter J. 1995b. *Astron. Astrophys.* 297:391–417

Neuhäuser R, Sterzik MF, Torres G, Martín E. 1995c. *Astron. Astrophys.* 299:L13–16

Neuhäuser R, Torres G, Sterzik MF, Randich S. 1997. *Astron. Astrophys.* 325:647–63

Neuhäuser R, Wolk SJ, Torres G, Preibisch T, Stout-Batalha NM, et al. 1998. *Astron. Astrophys* 334:873–94

Norman C, Heyvaerts J. 1985. *Astron. Astrophys.* 147:247–56

Ohashi N, Hayashi M, Ho PTP, Momose M, Hirano N. 1996. *Astrophys. J.* 466:957–63

O'Neal D, Feigelson ED, Mathieu RD, Myers PC. 1990. *Astron. J.* 100:1610–20

Ouyed R, Pudritz RE. 1997. *Astrophys. J.* 482:712–32

Paatz G, Camenzind M. 1996. *Astron. Astrophys.* 308:77–90

Palla F, Galli D. 1997. *Astrophys. J.* 476:L35–38

Park S, Finley JP. 1996. *Astron. J.* 112:693–99

Pasquini L, Cutispoto G, Gratton R, Major M. 1991. *Astron. Astrophys.* 248:72–80

Persi P, Olofsson G, Kaas AA, Nordh L, Bontemps S, et al. 1998. In *Star Formation with the Infrared Space Observatory*, eds. JL Yun, R. Liseau, Vol. 132, pp. 158–162. San Francisco: ASP

Phillips RB, Lonsdale CJ, Feigelson ED. 1991. *Astrophys. J.* 382:261–69

Phillips RB, Lonsdale CJ, Feigelson ED. 1993. *Astrophys. J. Lett.* 403:L43–45

Phillips RB, Lonsdale CJ, Feigelson ED, Deeney BD. 1996. *Astron. J.* 111:918–29

Pravdo SH, Angelini L. 1993. *Astrophys. J.* 407:232–36

Pravdo SH, Angelini L. 1995. *Astrophys. J.* 447:342–52

Pravdo SH, Marshall FE. 1981. *Astrophys. J.* 248:591–95

Preibisch T. 1997a. *Astron. Astrophys.* 320:525–39

Preibisch T. 1997b. *Astron. Astrophys.* 324:690–98

Preibisch T. 1998. *Astron. Astrophys.* 338:L25–28

Preibisch T, Zinnecker H, Herbig GH. 1996. *Astron. Astrophys.* 310:456–73

Preibisch T, Zinnecker H, Schmitt JHMM. 1993. *Astron. Astrophys.* 279:L33–36

Preibisch T, Neuhäuser R, Alcalá JM. 1995. *Astron. Astrophys.* 304:L13–16

Preibisch T, Neuhäuser R, Stanke T. 1998a. *Astron. Astrophys.* 338:923

Preibisch T, Guenther E, Zinnecker H, Sterzik M, Frink S, et al. 1998b. *Astron. Astrophys.* 333:619–28

Pudritz RE, Norman CA. 1983. *Astrophys. J.* 274:677–97

Pudritz RE, et al. 1999. In Mannings, et al. 1999. In press

Rao MN, Garrison DH, Palma RL, Bogard DD. 1997. *Meteorit. Plan. Sci.* 32:531–43

Ray TP, Muxlow TWB, Axon DJ, Brown A, Corcoran D, et al. 1997. *Nature* 385:415–17

Reale F, Betta R, Peres G, Serio S, McTiernan J. 1997. *Astron. Astrophys.* 325:782–90

Reipurth B, Bertout C, eds. 1997. *Herbig-Haro Flows and the Birth of Stars,* IAU Symp. 182, Dordrecht: Kluwer

Rice JB, Strassmeier KG. 1996. *Astron. Astrophys.* 316:164–72
Rodríguez LF. 1997. In *Herbig-Haro Flows and the Birth of Low Mass Stars*, eds. B Reipurth, C. Bertout, p. 83. Dordrecht: Kluwer
Romanova MM, Ustyugova GV, Koldoba AV, Chechetkin VM, Lovelace RVE. 1998. *Astrophys. J.* 500:703–13
Rucinski SM. 1992. *PASP* 104:311–13
Russell S, Wadhwa M. 1999. See Mannings et al. 1999.
Rydgren AE, Vrba FJ. 1983. *Astrophys. J.* 267:191–98
Ryter CE. 1996. *Astrophys. Sp. Sci.* 236:285–91
Safier PN. 1998. *Astrophys. J.* 494:336–41
Saguira N, Strangway D. 1988. In *Meteorites and the Early Solar System*, eds. JF Kerridge, MS Matthews, p. 595. Tucson, AZ: Univ. Ariz. Press
Schmitt JHMM. 1994. *Astrophys. J. Suppl.* 90:735–42
Schulz N, Berghöfer TW, Zinnecker H. 1997. *Astron. Astrophys.* 325:1001–12
Sciortino S, Favata F, Micela G. 1995. *Astron. Astrophys.* 296:370–79
Sciortino S, Damiani F, Favata F, Micela G. 1998. *Astron. Astrophys.* 332:825–41
Shang H, Shu FH, Glassgold AE. 1998. *Astrophys. J.* 493:L91–94
Shu FH, Adams FC, Lizano S. 1987. *Annu. Rev. Astron. Astrophys.* 25:23–81
Shu F, Najita J, Ruden SP, Lizano S. 1994. *Astrophys. J.* 429:781–96
Shu FH, Shang H, Glassgold AE, Lee T. 1997. *Science* 277:1475–79
Siess L, Forestini M, Dougados C. 1997. *Astron. Astrophys.* 324:556–65
Skinner SL. 1993. *Astrophys. J.* 408:660–67
Skinner SL, Brown A. 1994. *Astron. J.* 107:1461–68
Skinner SL, Güdel M, Koyama K, Yamauchi S. 1997. *Astrophys. J.* 486:886–902
Skinner SL, Walter FM. 1998. *Astrophys. J.* 509:761–67
Smith MA, Pravdo SH, Ku WH–M. 1983. *Astrophys. J.* 272:163–67
Smith KW, Lewis GF, Bonnell IA, Bunclark PS, Emerson JP. 1999. *MNRAS* 304:367–88
Spruit HC, Foglizzo T, Stehle R. 1997. *MNRAS* 288:333–42
Stapelfeldt KR, Krist JE, Ménard F, Bouvier J, Padgett DL, Burrows CJ. 1998. *Astrophys. J.* 502:L65–69
Sterzik MF, Alcalá JM, Neuhäuser R, Schmitt JHMM. 1995. *Astron. Astrophys.* 297:418–26
Sterzik MF, Durisen RH. 1995. *Astron. Astrophys.* 304:L9–12
Sterzik MF, Durisen RH, Brandner W, Jurcevic J, Honeycutt RK. 1997. *Astron. J.* 114:1555–66
Stine PC, Feigelson ED, André P, Montmerle T. 1988. *Astron. J.* 96:1394–1406
Stine PC, O'Neal D. 1998. *Astron. J.* 116:890–94
Stone RC, Taam RE. 1985. *Astrophys. J.* 291:183–87
Strassmeier KG, Welty AD, Rice JB. 1994. *Astron. Astrophys.* 285:L17–20
Strassmeier KG, Bartus J, Cutispoto G, Rodono M. 1997. *Astron. Astrophys. Suppl.* 125:11–63
Strom KM, Strom SE. 1994. *Astrophys. J.* 424:237–56
Strom KM, Strom SE, Edwards S, Cabrit S, Skrutskie MF. 1989. *Astron. J.* 97:1451–70
Strom K, Strom SE, Wilkin FP, Carrasco L, Cruz-González I, et al. 1990. *Astrophys. J.* 362:168–90
Suter M, Stewart RT, Brown A, Zealey W. 1996. *Astron. J.* 111:320–26
Svestka Z, Fárník F, Hudson HS, Uchida Y, Hick P, et al. 1995. *Sol. Phys.* 161:331–63
Tagliaferri G, Giommi P, Angelini L, Osborne JP, Pallavicini R. 1988. *Astrophys. J.* 331:L113–16
Tatischeff V, Ramaty R, Kozlovsky B. 1998. *Astrophys. J.* 504:874–88
Tayler RJ. 1987. *MNRAS* 227:553–61
Terebey S, Shu FH, Cassen P. 1984. *Astrophys. J.* 286:529–51

Tout CA, Pringle JE. 1996. *MNRAS* 281:219–25

Trimble V. 1996. In *Star Formation Near and Far*, ed. SS Holt, LG Mundy, p. 15–37. Woodbury, NY: AIP

Tsuboi Y, Koyama K, Murakami H, Hayashi M, Skinner S, et al. 1998. *Astrophys. J.* 503:894–901

Uchida T, Shibata K. 1984. *Pub. Astron. Soc. Japan* 37:515–35

van den Ancker ME, de Winter D, Thé PS. 1996. *Astron. Astrophys.* 313:517–22

Voit GM. 1992. *MNRAS* 258:841–48

Vrba FJ, Herbst W, Booth JF. 1988. *Astron. J.* 96:1032–39

Waelkens C, Waters LBFM. 1998. *Annu. Rev. Astron. Astrophys.* 36:233–66

Walter FM. 1986. *Astrophys. J.* 306:573–86

Walter FM, Brown A, Linsky JL, Rydgren AE, Vrba F, et al. 1987. *Astrophys. J.* 314:297–307

Walter FM, Brown A, Mathieu RD, Myers PC, Vrba FJ. 1988. *Astron. J.* 96:297–325

Walter FM, Kuhi LV. 1981. *Astrophys. J.* 250:254–61

Walter FM, Kuhi LV. 1984. *Astrophys. J.* 284:194–201

Walter FM, Vrba FJ, Mathieu RD, Brown A, Myers PC. 1994. *Astron. J.* 107:692–719

Walter FM, Vrba FJ, Wolk SJ, Mathieu RD, Neuhäuser R. 1997. *Astron. J.* 114:1544

Wasson J. 1993. *Meteoritics* 28:14

Webb RA, Zuckerman B, Platais I, Patience J, White RJ, et al. 1999. *Astrophys. J.* 512:L63–67

White GJ, Ricketts MJ. 1977. *Astrophys. Lett.* 18:79

White SM, Pallavicini R, Kundu MR. 1992b. *Astron. Astrophys.* 257:557–66

White SM, Pallavicini R, Kundu MR. 1992a. *Astron. Astrophys.* 259:149–54

Wichmann R, Krautter J, Schmitt JHMM, Neuhäuser R, Alcalá J, et al. 1996. *Astron. Astrophys.* 312:439–54

Wichmann R, Bouvier J, Allain S, Krautter J. 1998. *Astron. Astrophys.* 330:521–32

Wichmann R, Krautter J, Covino E, Alcalá JM, Neuhäuser R, Schmitt JHMM. 1997a. *Astron. Astrophys.* 320:185–95

Wichmann R, Sterzik M, Krautter J, Metanomski A, Voges W. 1997b. *Astron. Astrophys.* 326:211–17

Wolk SJ, Walter FM. 1996. *Astron. J.* 111:2066–76

Woolum DS, Hohenberg C. 1993. See Levy & Lunine 1993, pp. 903–19

Yamauchi S, Koyama K. 1993. *Astrophys. J.* 405:268–72

Yamauchi S, Koyama K, Inda-Koide M. 1994. *PASJ* 46:473–78

Yamauchi S, Koyama K, Sakano M, Okada K. 1996. *PASJ* 48:719–37

Yamauchi S, Hamaguchi K, Koyama K, Murakami H. 1998. *PASJ* 50:465–74

Yan M, Dalgarno A. 1997. *Astrophys. J.* 481:296–301

Zhekov SA, Palla F, Myasnikov AV. 1994. *MNRAS* 271:667–75

Zhou S, Evans NJ, Koempe C, Walmsley CM. 1993. *Astrophys. J.* 404:232–76