CORONAL X-RAY EMISSION FROM AN INTERMEDIATE-AGE BROWN DWARF

YOHKO TSUBOI
Department of Science and Engineering, Chuo University, Kasuga 1-13-27, Bunkyo-ku, Tokyo 112-8551, Japan; tsuboi@phys.chuo-u.ac.jp

YOSHIKICHI MAEDA
High Energy Astrophysics Division, Institute of Space and Astronautical Science, Yoshinodai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan; ymaeda@is.as.ac.jp

ERIC D. FEIGELSON, GORDON P. GARMIRE, GEORGE CHARTAS, AND KOJI MORI
Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802; efd@astro.psu.edu, garmire@astro.psu.edu, chartas@astro.psu.edu, mori@astro.psu.edu

AND

STEVEN H. PRAVDO
Jet Propulsion Laboratory, Mail Stop 306-438, California Institute of Technology, Pasadena, CA 91109; spravdo@jpl.nasa.gov

Received 2002 December 20; accepted 2003 February 28; published 2003 March 12

ABSTRACT

We report the X-ray detection of the brown dwarf (BD) companion TWA 5B in an $\sim$12 Myr old pre–main-sequence binary system. We clearly resolve the faint companion (35 photons) separated from the X-ray luminous primary by 2\" in a Chandra ACIS image. TWA 5B shows a soft X-ray spectrum with a low plasma temperature of only 0.3 keV and a constant flux during the 3 hr observation, of which the characteristics are commonly seen in the solar corona. The X-ray luminosity is $4 \times 10^{27}$ ergs s$^{-1}$ (0.1–10 keV band) and log ($L_X/L_{bol}$) $\approx$ −3.4. Comparing these properties to both younger and older BDs, we discuss the evolution of the X-ray emission in BDs. During their first few megayears, they exhibit high levels of X-ray activity, as seen in higher mass pre–main-sequence stars. The level in TWA 5B is still high at $t \approx 12$ Myr in log ($L_X/L_{bol}$), while $kT$ has already substantially cooled.

Subject headings: stars: coronae — stars: individual (CD $-$33°7795B, TWA 5B) — stars: low-mass, brown dwarfs — X-rays: stars

On-line material: color figure

1. INTRODUCTION

With masses below the hydrogen-burning mass limit $M < 0.08 M_\odot$ and cool, nearly neutral surfaces, brown dwarfs (BDs) had been expected to lack high-energy activity. However, X-rays from several young BDs with ages $t \sim$ 1 Myr old were discovered with ROSAT in nearby star-forming regions (Neuhäuser & Comerón 1998; Neuhäuser et al. 1999; Mokler & Stelzer 2002). After the launch of the Chandra X-Ray Observatory, the number of X-ray–detected young BDs has increased at an order of magnitude (Garmire et al. 2000; Imanishi, Koyama, & Tsuboi 2001a; Imanishi, Tsujimoto, & Koyama 2001b; Freibisch & Zinnecker 2001; Feigelson et al. 2002). In young stellar clusters around 1 Myr old, hard and variable X-rays are now detected from about one-fourth of the BD population near the “saturation level” of log ($L_X/L_{bol}$) $\approx$ −3. These properties are indistinguishable from those of higher mass young objects, which will evolve into dM stars.

Nearby field L- and T-type older BDs with ages $t \approx$ 500–1000 Myr lack Hα emission, a classical signature of active regions and plage, but indicate radio flares (Gizis et al. 2000; Berger 2002). The weak Hα in field BDs is particularly surprising in light of their rapid rotation (Basri 2001). One field BD at age $t \approx$ 500 Myr, however, is clearly magnetically active. LP 944-20 showed a 1–2 hr flare during a Chandra observation with a peak luminosity $L_X = 1 \times 10^{26}$ ergs s$^{-1}$ [log ($L_X/L_{bol}$) $\approx$ −4.1] with a surprisingly soft spectrum, while it exhibited no detectable quiescent X-rays before the flaring (Rutledge et al. 2000). This BD also has exceptionally strong radio emission (Berger et al. 2001) and shows Hα emission of EW $\sim$ 1 Å (Tinney 1998). At the intermediate age of $t \approx 100$ Myr, three probable BDs in the Pleiades have been observed with XMM-Newton, of which one, Roque 9, may have been detected at log ($L_X/L_{bol}$) $\approx$ −2.6 (Briggs & Pye 2003; Stelzer & Neuhäuser 2003).

The evolution of magnetic activity in BDs thus appears confusing: Hα and X-rays appear to decay as they descend the Hayashi tracks and cool, while radio emission does not. The nonthermal radio emission is particularly puzzling, with both flare and persistent components far stronger than expected from the well-established Güdel-Benz radio/X-ray relationship that holds for all other late-type stars (Berger 2002). This contrasts with the theoretical expectation that BD surface magnetic activity should decay with age because of increased resistivity of the atmosphere (Mohanty et al. 2002). The evolution of magnetic activity in higher mass late-type stars is also not fully understood. Various multiwavelength manifestations of magnetic activity (X-ray flares, radio flares, Hα emission, large starspots, strong surface fields, etc.) are consistently seen at high levels in T Tauri stars but do not appear to depend on rotation, as seen in main-sequence stars (Feigelson & Montmerle 1999; Feigelson et al. 2003).

We introduce to this issue the Chandra detection of TWA 5B, a BD at the intermediate age of $t \approx$ 12 Myr. TWA 5B is a faint red object ($H = 12$ mag) located 2° north of and comoving with TWA 5A, which itself is a spectroscopic binary (Lowrance et al. 1999; Webb et al. 1999; Neuhäuser et al. 2000). This system is part of the dispersed TW Hydra Association (TWA) of T Tauri stars, all of which are likely outliers of the giant Sco-Cen OB association (Kastner et al. 1997; Majewski, Lawson, & Feigelson 2000). TWA 5 is the first identified pre–main-sequence (PMS) star–BD binary system with an estimated age of 12 ± 6 Myr (Weintraub et al. 2000). We assume
here the mean *Hipparcos* distance to the four brightest TWA members of 55 pc. Optical and near-infrared photometry of TWA 5B gives a spectral type of M8.5–M9 and bolometric luminosity $\log (L_{\text{bol}}/L_\odot) \approx -2.6 \pm 0.3$, giving an inferred mass between 15 and 40 $M_\text{Jup}$ (Neuhaüser et al. 2000). The EW of Hα $\approx 20$ Å lies between those of young BDs (10–100 Å at $\approx$1 Myr old) and those of field BDs ($\approx$1 Å at $\approx$500–5000 Myr). TWA 5B is thus clearly an intermediate-age BD and may be near the end of its brief deuterium-burning phase (Weintraub et al. 2002 for a description of the satellite and instrument). The S3 CCD chip was operated in a rapid readout subarray mode to reduce photon pileup of the primary TWA 5A (see Weisskopf et al. 2002 for a description of the satellite and instrument). The *Chandra* X-Ray Observatory (e.g., Imanishi et al. 2001a) shows very strong emission with about 6200 counts from TWA 5B, a CCD readout stripe oriented northeast/southwest, and a faint excess of events $2^\circ$ to the north where TWA 5B lies. The TWA 5B emission becomes much clearer after the special processing steps outlined above. Figure 1 (middle) shows this X-ray image in a very soft 0.1–1.2 keV band that highlights the emission from the BD companion. Note that a resolution of $\approx0.3$ FWHM is achieved using the subpixel process, while the original data have $\approx0.5$ FWHM (these FWHM values are measured from a radial profile binned by 0.05 pixel.)

We extracted 35 photons from the standard level 2 event list around TWA 5B in the 0.1–8 keV band using a 0.5” radius circle after removal of background from an annulus around TWA 5A (see Fig. 1, right). Since the extracted region is smaller than the standard *Chandra* point-spread function at this position, a modified “auxiliary reference file” was created. The background-subtracted spectrum of TWA 5B was fitted with an optically thin MEKAL thermal plasma model with elemental abundances fixed at 0.3 times of the solar value, based on the fitting results of other young stellar objects (YSOs) detected by *Chandra* and ASCA (e.g., Imanishi et al. 2001a). The resulting spectrum, shown in Figure 2, is unusually soft, with peak emission at 0.7 keV and no photons above 1.5 keV. Best-fit parameters with 90% confidence levels are temperature $kT = 0.3_{-0.2}^{+0.2}$ keV, line-of-sight column density $N_\text{H} < 6 \times 10^{20}$ cm$^{-2}$, emission measure $(4 \pm 1) \times 10^{58}$ cm$^{-3}$, and luminosity $L_X = 4 \times 10^{32}$ ergs s$^{-1}$ in the 0.1–8 keV band. The spectral fit was essentially perfect, with a reduced $\chi^2$ of 0.5 for 3 degrees of freedom. The plasma temperature and the luminosity are close to typical plasma conditions in the Sun today; at solar maximum, typical temperatures are $kT \approx 0.2–0.5$ keV with $L_X \approx 1 \times 10^{32}$ ergs s$^{-1}$ (Peres et al. 2000). During a powerful solar flare, the typical temperatures rise to $T \approx 1–2$ keV, much hotter than seen in TWA 5B but typical of other PMS stars and BDs (e.g., Feigelson et al. 2002).

A light curve of the photon arrival times was examined and no significant variations were found during the 11 ks duration of the observation. We can exclude variations greater than 50% in amplitude over the 10 ks observation.

---

**Fig. 1.** — TWA 5 system showing the intermediate-age BD TWA 5B just north of the primary star; 1-band image from Neuhaüser et al. 2000 (left), *Chandra* X-ray image (0.1–2 keV) obtained here (middle); and the diagram of the X-ray spectral extraction regions (right). The *Chandra* image is displayed in 0.1 pixels after special processing steps outlined in the text and smoothing with a 0.75 FWHM Gaussian. [See the electronic edition of the Journal for a color version of this figure.]

---

**Fig. 2.** — ACIS spectrum of TWA 5B extracted from a 0’’7 radius region after background subtraction (see Fig. 1, right). The spectrum is fitted with a coronal plasma model, and the bottom panel shows the residuals from the best-fit model.
3. DISCUSSION

3.1. Evolution of X-Ray Emission

As outlined in the Introduction, there is considerable confusion in our understanding of the evolution of BD magnetic activity. Figure 3 shows our current knowledge of the relationship between X-ray emission, parameterized as $L_X/L_{bol}$, and the age of BDs. The X-ray properties for BDs in the Orion Nebula, ρ Ophiuchi, and IC 348 are obtained from Chandra ACIS data by Feigelson et al. (2002), Imanishi et al. (2001b), and Preibisch & Zinnecker (2001), respectively. The field BD LP 944-20 detection is from Rutledge et al. (2000). Individual BD ages are distributed randomly for 1 order of magnitude centered on 0.4 Myr (ρ Oph and Orion) and 1.5 Myr (IC 348) based on Luhman et al. (2000). For Orion, the upper limits of X-ray–undetected BDs were obtained as described in Feigelson et al. (2002, eqs. [7] and [10]), assuming negligible absorbing column and bolometric luminosities from Hillenbrand & Carpenter (2000). The data of LP 944-20 are separately shown for the flare, the upper limit at the quiescent (preflare) phase, and the time average during full observation, while the others are shown only for the last one (full observations). Except for LP 944-20, only two sources in ρ Oph and one in IC 348 have clear flares with amplitudes less than a factor of 10, which are within the range of the data scattering of each field. TWA 5B at log $(L_X/L_{bol}) = -3.4$ lies just below the $-3.0$ saturation limit in main-sequence clusters and is consistent with the BDs seen in younger clusters.

Although a clear conclusion cannot be made from one object, this result is consistent with a continued high level of BD X-ray surface activity through $t \approx 12$ Myr. The decay to lower levels would then occur during the $10^6–10^7$ yr phase, considering the averaged level of LP 944-20. This is consistent with the nearly constant (or even slightly rising; see Feigelson et al. 2003) log $(L_X/L_{bol})$ distribution from $t < 1$ Myr through $t \approx 20$ Myr seen in higher mass late-type stars. The high level in log $(L_X/L_{bol})$ in the younger phase might be related to the deuterium burning, with the fact that TWA 5B lies just at the end of the burning phase (Weintraub et al. 2000).

A somewhat different result emerges from consideration of the relationship between X-ray plasma temperature and age in BDs (Fig. 4). Here the temperatures are derived from spectral fits to Chandra ACIS data by the authors listed above. While very young BDs have hotter temperatures above 1 keV, the intermediate-age BD TWA 5B is significantly cooler at $kT \approx 0.3$ keV, similar to the temperature found in the flare of the older LP 944-20 (Rutledge et al. 2000). However, the low temperature in TWA 5B, combined with the lack of variability, suggests that its X-ray emission arises more from a "corona" than a single "flare."

While a similar trend from hotter plasma to cooler plasma is seen in higher mass YSOs, the timescale for this transition is much longer than implied for BDs. X-ray temperatures are typically $kT = 6$ keV for protostars (e.g., Imanishi et al. 2001a) and $kT = 1–4$ keV for typical T Tauri stars (e.g., Feigelson et al. 2002), with highly variable flare-dominated light curves. This hotter plasma is dominated by cooler coronal plasma only after $\approx 500$ Myr (Güdel, Guinan, & Skinner 1997).

It is interesting that the plasma temperature in LP 944-20 flaring is similar to that in TWA 5B quiescent. Considering that the X-ray luminosity of the LP 944-20 flaring is at least an order of magnitude less than that of TWA 5B quiescent, the X-rays of TWA 5B, which appear as coronal emission, might be explained by a superposition of a number of such small flares. The similar possibility has been suggested and examined for the solar corona (Parker 1988; Shimizu & Tsuneta 1997).

3.2. Comments on the Relationship between X-Ray and Hα Emissions

Figure 5 shows our current knowledge of the relationship between X-ray emission, parameterized as $L_X/L_{bol}$, and the Hα EWs of BDs. In this plot, the ordinate indicates the X-ray surface brightness at the BD surface, while the abscissa represents the Hα surface brightness, in the zeroth order. Here the Hα properties are obtained from Jayawardhana, Mohanty, & Basri (2002) for BDs in the ρ Ophiuchi, Luhman (1999) and Herbig (1998) for those in IC 348, and Tinney (1998) for the field BD LP 944-20. For the time-averaged X-rays of detected BDs, we obtained a correlation of log $(L_X/L_{bol}) = 1.5 \log \text{Hα} – 5.3$. Such correlation has been already known in higher mass weak-lined T Tauri stars (for a recent example, see Preibisch & Zinnecker 2002), which is interpreted by the hypothesis that the chromo-
sphere (traced by the Hα activity) is heated by a sufficient overlying corona (X-ray activity; Cram 1982).

Figure 5 also shows that the strongest six (∼100 Å) in the Hα EW were not detected in X-rays. As with higher mass classical T Tauri stars, these strong emission lines would be accompanied by IR disks. The relation given in Figure 5 is thus straightforwardly interpreted by the scenario that X-rays are due mainly to the coronal activity, while Hα is dominated by the chromospheric activity (approximately less than a few tens of Å) and by the disk activity (approximately greater than a few tens of Å). These nondetections also suggest that BD X-ray activity does not likely originate from star-disk interaction but from the solar-like magnetic activity.

4. CONCLUSION

We report the detection of X-rays from an intermediate-age (t ≈ 12 Myr) BD at a level of $L_X \approx 4 \times 10^{27}$ ergs $^{-1}$ (0.1–10 keV band) or $\log (L_X/L_{bol}) = -3.4$. The X-ray spectrum is very soft; the dominant plasma temperature is only 0.3 keV. No variability is seen during the 10.3 ks observation. Those characteristics are common to those in the solar corona. Our observation provides a link between the active state seen in younger t ≈ 1 Myr stellar clusters and a relatively inactive state, showing continuity in the evolution of both X-ray luminosity and plasma temperature; log $(L_X/L_{bol})$ has not yet decayed by t ≈ 12 Myr, while $kT$ has already substantially cooled. The correlation between X-rays and Hα implies the idea that the X-rays are due mainly to the coronal activity, while Hα is dominated by the chromospheric activity (approximately less than a few tens of Å) and by the disk activity (approximately greater than a few tens of Å). Finally, we note that since TWA 5B is not far from the boundary between BDs and the most massive planets found orbiting nearby stars, it raises the possibility that massive planets might emit X-rays during their youth.

We express our thanks to the Chandra team for many efforts toward the fabrication of the satellite, launching, daily operation, software developments, and calibrations. We also thank Leisa Townsley for supplying the CTI corrector of ACIS and Kensuke Inamishii and the referee Gabor Basri for useful comments on brown dwarf flares and coronae. This research was supported by NASA contract NAS 8-38252.

REFERENCES

Basri, G. 2001, in ASP Conf. Ser. 223, Cool Stars, Stellar Systems and the Sun: 11th Cambridge Workshop, ed. R. J. García López, R. Rebolo, & M. R. Zapatero Osorio (San Francisco: ASP), 261
Berger, E. 2002. ApJ, 572, 503
Berger, E., et al. 2001, Nature, 410, 338
Briggs, K. R., & Pye, J. P. 2003, in ASP Conf. Ser. 277, Stellar Coronae in the Chandra and XMM-Newton Era, ed. F. Favata & J. J. Drake (San Francisco: ASP), in press (astro-ph/0110109)
Cram, L. E. 1982. ApJ, 253, 968
Feigelson, E. D., Broos, P., Gaffney, J. A., Garmire, G., Hillenbrand, L. A., Pravdo, S. H., Townsley, L., & Tsuibo, Y. 2002, ApJ, 574, 258
Feigelson, E. D., Gaffney, J. A., Garmire, G., Hillenbrand, L. A., & Townsley, L. 2003, ApJ, 584, 911
Feigelson, E. D., & Montmerle, T. 1999, ARA&A, 37, 363
Garmire, G., Feigelson, E. D., Broos, P., Hillenbrand, L. A., Pravdo, S. H., Townsley, L., & Tsuibo, Y. 2000, AJ, 120, 1426
Grizis, J. E., Monet, D. G., Kirkpatrick, J. D., Liebert, J., & Williams, R. J. 2000, AJ, 120, 1085
Güdel, M., Guinan, E. F., & Skinner, S. L. 1997, ApJ, 483, 947
Herdig, G. H. 1998, ApJ, 497, 736
Hillenbrand, L. A., & Carpenter, J. M. 2000, ApJ, 540, 236
Imanishi, K., Koyama, K., & Tsuibo, T. 2001a, ApJ, 557, 747
Imanishi, K., Tsujimoto, M., & Koyama, K. 2001b, ApJ, 563, 361
Jayawardhana, R., Mohanty, S., & Basri, G. 2002, ApJ, 578, L141
Kastner, J. H., Zuckerman, B., Weintraub, D. A, & Forveille, T. 1997, Science, 277, 67
Lowrance, P. J., et al. 1999, ApJ, 512, L69
Luhman, K. L., Rieke, G. H., Young, E. T., Cotera, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, ApJ, 540, 1016
Mamajek, E. E., Lawson, W. A., & Feigelson, E. D. 2000, ApJ, 544, 356
Mohanty, S., Basri, G., Shu, F., Allard, F., & Chabrier, G. 2002, ApJ, 571, 469
Mokler, F., & Stelzer, B. 2002, A&A, 391, 1025
Mori, K., Tsunemi, H., Miyata, E., Baluta, C. J., Burrows, D. N., Garmire, G. P., & Chartas, G. 2001, in ASP Conf. Ser. 251, New Century of X-Ray Astronomy, ed. H. Inoue & H. Kunieda (San Francisco: ASP), 576
Neuhäuser, R., et al. 1999, A&A, 343, 883
Neuhäuser, R., & Comerón, F. 1998, Science, 282, 83
Neuhäuser, R., Guenther, E. W., Petr, M. G., Brandner, W., Hüélamo, N., & Alves, J. 2000, A&A, 360, L39
Parker, E. N. 1988, ApJ, 330, 474
Peres, G., Orlando, S., Reale, F., Rosner, R., & Hudson, H. 2000, ApJ, 528, 537
Preibisch, T., & Zinnecker, H. 2001, AJ, 122, 866
Rutledge, R. E., Basri, G., Martin, E. L., & Bildsten, L. 2000, ApJ, 538, L141
Shimizu, T., & Tsuneta, S. 1997, ApJ, 486, 1045
Stelzer, B., & Neuhäuser, R. 2003, in IAU Symp. 211, Brown Dwarfs, ed. E. Martin (San Francisco: ASP), in press (astro-ph/0206284)
Tinney, C. G. 1998, MNRAS, 296, L42
Townsley, L. K., Broos, P. S., Garmire, G. P., & Chartas, G. 2001, in ASP Conf. Ser. 251, New Century of X-Ray Astronomy, ed. H. Inoue & H. Kunieda (San Francisco: ASP), 576
Van Speybroeck, L. P. 2002, PASP, 114, 1
Weisskopf, M. C., Brinkman, B., Canizares, C., Garmire, G., Murray, S., & Van Speybroeck, L. P. 2002, PASP, 114, 1