Brown Dwarfs
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X-Ray Detection of Brown Dwarfs with Chandra

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Abstract. I review recent observations of brown dwarfs by the *Chandra* X-ray Observatory. These observations fall in 2 categories, young stellar clusters which contain brown dwarfs and brown dwarf candidates and directed pointings at brown dwarfs and very low mass stars. Surprisingly, there are already over 60 published detections of brown dwarfs by *Chandra.* A review of the X–ray characteristics shows these objects are subject to flaring and their temperatures and luminosities have a vast range which is related to age.

1. Introduction

Young stars can emit up to 0.1% of their energy in the X-ray band. These X-rays are thought to be formed in a solar–like $\alpha - \Omega$ dynamo, so called, because the magnetic field is thought to be wound by stellar rotation and by twists within the latitudinal field. Such a dynamo requires a radiative core to anchor the field. However, young stars without cores (later than M2.5), are seen to have similar X–ray phenomena. New mechanisms, including $\alpha - \alpha$ or turbulent dynamos, have been called upon to explain activity observed by ROSAT in stars as late as M7 – brown dwarfs. With the *Chandra* X-ray Observatory, it is now possible to detect X-rays from less massive and older brown dwarfs.

2. X–rays from Brown Dwarfs

Using ROSAT data, Neuhäuser & Comerón (1998) discovered the first X-ray emitting brown dwarfs in the $\sim$ 1 million year old Chamaeleon cluster. They have luminosities, in units of bolometric luminosity, about 1-10% the value found for young M5 stars. A later archival survey by Neuhäuser et al. (2000) discovered X-rays from the brown dwarf GY 202 in ρ Oph and 4 other brown dwarf candidates.

ROSAT unambiguously detected X-rays from brown dwarfs, but search for X-rays from brown dwarfs is more than just astronomical limbo ("how low can you go?"). It is an attempt to understand the inner workings and evolution of very cool bodies. It is known that X-ray luminosity is highly dependent on age. The ROSAT findings now indicate a fundamental change in the nature of the magnetic field as a function of spectral type between M7 and M8, while none is seen between M2 and M3. This is disagreement among other tracers of magnetic activity among very-late type PMS stars. About 0.01% of the stellar luminosity of young stars comes out in Hα until about M6-7, at which point the relative Hα flux plummets (Gizis et al. 2001). On the other hand, radio luminosities, which trace X-rays from stars in a simple power law from F types to as late as M7, are seen to increase beyond the end of the main sequence (Berger et al. 2002).

3. Brown Dwarfs in Clusters

The most efficient method for finding brown dwarfs, in the X-ray or any other regime, is to look in nearby young massive clusters where there are many, relatively bright candidate objects in the field. To date, several such clusters have been reported on. Table 1 summarizes the current discoveries of brown dwarfs in clusters. Space permits the discussion of three of these.

Table 1. CXO Detections of Brown Dwarfs in Young Clusters.

Region	Age	Detections		<Energy>	<Luminosity>
	(Myr)	Candidates	bona-fide	keV	L_X/L_{bol}
M42	0-1	30/100	1/15	1-4	-4
IC 348	1	3/12	3/13	1-1	-3.5
ρ Oph	0–3	5/10	1/8	1-2	-4.7
Pleiades[1]	~100	0/10	– –	– –	– –

[1] Krishnamurthi et al. 2001.

- M42 - The ONC has been observed with both the Advanced CCD Imaging Spectrograph (ACIS) and the High Resolution Camera (HRC). In the HRC study Flaccomio et al. (2002) confined their brown dwarf study to 15 spectroscopically confirmed brown dwarfs (Lucas et al. 2001). They detect one, but by superposing events from the location of the undetected sources, a composite source is revealed indicating that these brown dwarfs do not depart from the L_X–mass relationship seen in higher–mass cluster members. The ACIS study (Feigelson et al. 2002) searches for X-rays from about 100 brown dwarf candidates with 30 detections. ACIS has intrinsic spectral resolution, so temperatures of these sources can be measured and are found to be in the 1-4 keV range. There will be an additional observation of this cluster in early 2003 increasing the total exposure time by a factor of 10.

- IC 348 - This cluster is slightly lower in mass than the ONC. The 50 ks observation has been thoroughly analyzed by Preibisch and Zinnecker (2001, 2002). They detected 4/13 bona-fide brown dwarfs and 3/12 brown dwarf candidates in the field. All detections had less than 20 counts, so detailed analysis is difficult. As in the case of the ONC, coronal temperatures are again found to be hot (1–2 keV), and luminosities are consistent with those of higher mass stars. There is also evidence of X-ray variability among these sources.

- ρ Oph - This embedded cluster has been subject of two deep (100 ks) pointings. Imanishi et al. (2001) have looked for detections among the 18 brown dwarfs and brown dwarf candidates in the field. They found five, again the sources were hot (1–2 keV) and fairly luminous. The brightest is GY 31, having nearly 400 photons detected. In this case, the bulk of the photons arrived during a 10 ks flare. One other source had flare–like emission. The previously detected GY 202 was not detected by CXO.

4. Isolated Brown Dwarfs

While young clusters are efficient places to find bright sources, they do not necessarily reflect the nature of the objects later in life. This problem is especially acute in the case of brown dwarfs. These objects are constantly evolving. The characteristics at a certain age and mass will change in time. Thus a study of field brown dwarfs is needed to truly understand these objects. Most of these studies have taken place with the ACIS-S detector. This differs from the ACIS-I array used for most cluster observations because ACIS-S is more sensitive to lower energy X-rays than ACIS-I and still has the spectral resolution that the HRC lacks.

The first nearby brown dwarf detected by CXO was LP 944-20. This is a 60 M_{jup} body about 500 Myr old located within 5 pc of the Sun. Rutledge et al. (2000) performed a 50 ks observation and detected the source. Examination of the data showed that 15 of the 19 counts arrived during a single 5 ks flare. The flare itself was quite cool ($\sim$ 260 eV) and the X-ray luminosity during the flare was about $L_X/L_{bol} = 10^{-4.5}$. The quiescent luminosity is found to be $L_X/L_{bol} < 2 \times 10^{-6}$.

Table 2 summarizes the current results among low mass field stars. Jupiter is included on this table as an extreme example of old age and low mass. The disk of Jupiter has been detected with the HRC. The flux from the disk, poles excluded, is about 7×10^{15} egs/s. While X-rays from Jupiter's poles are explained as complex interactions with the solar wind, the general surface emission for the cool neutral atmosphere is unexplained.

Table 2. CXO Detections of Very Low Mass Field Objects.

Star	Age (Myr)	Mass $M_\odot$	<Energy> (keV)	<Luminosity> Log (L_X/L_{bol})	Notes
VB 8	> 1Gyr	0.11	<< 1.0	-4.2	
VB 10	> 1Gyr	0.09	<< 1.0	-4.8	(1)
LP 944-20	500 Myr	0.05	0.26	-4.5	(2)
TWA 5B	10 Myr	0.02	0.3	-3.3	(3)
Jupiter	4.5 Gyr	0.01	NA	NA	(4)

(1) seen to flare; (2) seen only in flare; (3) preliminary; (4) surface emission.

5. Status and Future Observations

As seen in the previous two sections, the results to date seem to bifurcate. VLM stars in young clusters, tend to look like low–mass stars. Perhaps the majority of brown dwarfs do not saturate their coronae as solar mass PMS stars do, but they are quite bright (Log (L_X/L_{bol}) $\sim -4.0 - - - 3.5$) and hot (E$\sim$ 2 eV).

Older field stars are different. Even at ages as young as 10 Myr,temperatures are less than a keV and the objects tend to be seen only in flares.

There are several explanations as to why the characteristics are so different. One is intrinsic and the other instrumental. Taking the latter first, stellar clusters tend to be observed with the wide-field of view configuration ACIS-I. ACIS-I has little sensitivity below 500 eV. Meanwhile, field brown dwarfs are observed with ACIS-S which has better sensitivity below 500 eV. Hence we are finding what we are sensitive to. Perhaps there are two components to the coronae of VLM stars; a cool one, intrinsic to the body, and a warmer one caused by a fossil magnetic field.

The intrinsic differences between the cluster brown dwarfs and the field ones are their age and temperature. As VLM bodies age, they rapidly become much later spectral types. This changes the atmosphere as which becomes dominated by neutral species. Very late spectral types also have a different interior structure as degeneracy will set in. The decay of activity with age is well studied for low mass stars and has a time scale of about 100 Myr as stars lose their angular momentum to winds. But why does the activity decrease as the brown dwarfs age just 10 million years?

In addition to the observations discussed here, there are several other observations planned as well as those in the archive which are still within their proprietary period. In the next two years there will be pointed observations of three L class stars and two M9 stars. The σ Orionis cluster is planned for fall 2002. This observation takes advantage of the low energy sensitivity of HRC and the unobscured nature of the σ Orionis cluster to allow detection of soft sources not possible in other cluster observations. In addition, there are archived cluster studies of Chamaeleon I North and the fields flanking the ONC. One part of Chandra's legacy will be the investigation of these faint and clustered sources and perhaps a better understanding of the changes in the interior structure of young, low-mass, constantly evolving bodies.

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References

Berger, E. 2002, ApJ, 572, 503.
Feigelson, E.D. et al. 2002, ApJ, 574, 258.
Flaccomio, E. et al. 2002, ApJ *accepted.*
Gizis, J.E. et al. 2001, AJ, 120, 1085.
Imanishi, K. et al. , 2001, ApJ, 563, 361.
Krishnamurthi, A. et al. 2001 AJ, 121, 337.
Lucas, P.W. et al. 2001, MNRAS, 326, 695.
Neuhäuser, R. & Comerón, F. 1998, Science, 202, 83.
Neuhäuser, R. et al. 1999, A&A, 343, 883.
Preibisch, T. & Zinnecker, H. 2001, AJ, 122, 866.
Preibisch, T. & Zinnecker, H. 2002, AJ, 123, 1613.
Rutledge, R.E. et al. 2000, ApJ, 538, L141.