

# Discovery of X-ray emission from the eclipsing brown-dwarf binary 2MASS J05352184-0546085

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## ABSTRACT

The eclipsing brown-dwarf binary system 2MASS J05352184-0546085 is a case sui generis. For the first time, it allows a detailed analysis of the individual properties of young brown dwarfs, in particular, masses, and radii, and the temperature ratio of the system components can be determined accurately. The system shows a “temperature reversal” with the more massive component being the cooler one, and both components are found to be active. We analyze X-ray images obtained by *Chandra* and XMM-*Newton* containing 2MASS J05352184-0546085 in their respective field of view. The *Chandra* observatory data show a clear X-ray source at the position of 2MASS J05352184-0546085, whereas the XMM-*Newton* data suffer from contamination from other nearby sources, but are consistent with the *Chandra* detection. No indications of flaring activity are found in either of the observations (together  $\approx 70$  ks), and we thus attribute the observed flux to quiescent emission. With an X-ray luminosity of  $3 \times 10^{28}$  erg/s we find an  $L_X/L_{\text{bol}}$ -ratio close to the saturation limit of  $10^{-3}$  and an  $L_X/L_{\text{H}\alpha}$ -ratio consistent with values obtained from low-mass stars. The X-ray detection of 2MASS J05352184-0546085 reported here provides additional support for the interpretation of the temperature reversal in terms of magnetically suppressed convection, and suggests that the activity phenomena of young brown dwarfs resemble those of their more massive counterparts.

**Key words.** stars: low-mass, brown dwarfs – stars: binaries: eclipsing – stars: activity – X-rays: individuals: 2MASS J05352184-0546085

## 1. Introduction

Magnetic activity is extremely common among late-type stars with outer convection zones (e.g., Schmitt 1997). The cause of that activity as diagnosed by chromospheric and coronal emissions is ultimately thought to be a magnetic dynamo operating near the base of the convection zones of these stars. Near the spectral type  $\sim M3$ , stars are thought to become fully convective, thereby preventing the emergence of a solar like dynamo in their interiors, and yet the activity properties seem to remain unchanged across this borderline (e.g. Fleming et al. 1993). A saturation level of  $L_X/L_{\text{bol}} \sim 10^{-3}$  is observed also for fully convective stars, although with substantial dispersion. Ultra cool dwarfs (spectral type M7 and later) show a drop in activity as measured through their  $H_\alpha$  emission, and among L-type dwarfs  $H_\alpha$  emission is rarely found (Gizis et al. 2000). For the majority of active M dwarfs the ratio between  $H_\alpha$  and bolometric luminosity is  $\log(L_{\text{H}\alpha}/L_{\text{bol}}) \sim -3.8$ , while for most objects of spectral class L this ratio drops below  $-5$ . Mohanty et al. (2002) argue that the high degree of neutrality in the outer atmospheres of very low-mass stars effectively diminishes the activity level with effective temperature.

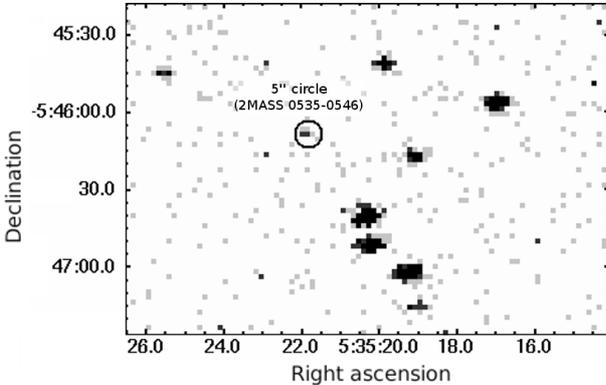
X-ray detections from ultra cool dwarfs are quite sparse, and only a few objects have been identified as X-ray sources during flaring and quiescent periods. Examples comprise the binary system GJ 569 B consisting of two evolved (age  $\approx 500$  Myr) substellar objects of late-M spectral type detected by Stelzer (2004) and the latest (with respect to spectral type) object being the M9 dwarf LHS 2065 (e.g., Schmitt & Liefke 2002; Robrade & Schmitt 2008). Hence, the behavior of X-ray

emission is unclear as one approaches the boundary towards the substellar brown dwarfs and also the role played by the different stellar parameters for the activity evolution of these objects remains unclear (Stelzer & Micela 2007). It is particularly surprising that some of the very rapidly rotating substellar objects show little or no signs of activity. During the very early phases of their evolution, however, when the optical characteristics of brown dwarfs resemble those of stars with spectral type M6 or so, they are often found to be quite active. Starting with the first X-ray detection of Cha H $\alpha$  1 in the Chamaeleon I star forming region (Neuhauser & Comeron 1998), quite a number of brown dwarfs settled in star forming regions and (young) clusters have been detected in X-rays. The detection rate is higher for young brown dwarf compared to evolved ones, which might be related to a higher intrinsic X-ray luminosity, hotter outer atmospheres, or both.

A crucial advance in the observational endeavor to unravel the nature of low-mass objects was the discovery of an eclipsing brown-dwarf binary (“2MASS J05352184-0546085” – in the following 2MASS 0535-0546, Stassun et al. 2006), which allowed to directly measure masses, radii, and a temperature ratio for brown dwarfs for the first time. The 2MASS 0535-0546 system is thought to be a member of the Orion Nebular Cluster (ONC) and, hence, very young (age  $\approx 10^6$  years). It consists of two  $M 6.5 \pm 0.5$  dwarfs in an eccentric ( $e = 0.31$ ) 9.78 day orbit, such that the two eclipses are separated by a phase difference of 0.67. In their analysis of 2MASS 0535-0546 Stassun et al. (2006) determine masses of  $M_1 = 56 \pm 4 M_{\text{Jup}}$  and  $M_2 = 36 \pm 3 M_{\text{Jup}}$  as well as radii of  $R_1 = 0.67 \pm 0.03 R_\odot$  and

**Table 1.** X-ray data of 2MASS 0535-0546.

Instr.	ID	Obs. time [ks]	Obs. date [MJD]
<i>Chandra</i>	2548	48.5	52 523.54
<i>XMM-Newton</i>	0112660101	22.1	52 167.08

**Fig. 1.** X-ray image (2 arcsec/bin) of the surrounding of 2MASS 0535-0546. A circular (5 arcsec radius) region centered on the nominal target position is superimposed on the image.

$R_2 = 0.49 \pm 0.02 R_\odot$  for the primary and secondary component, respectively. Astonishingly, a “temperature reversal” is observed in this system, i.e., the higher-mass primary component was found to be cooler than its lower-mass companion ( $T_1 \approx 2700$  K and  $T_2 \approx 2800$  K, Stassun et al. 2007; Reiners et al. 2007).

From the activity point of view 2MASS 0535-0546 is particularly interesting since both components appear to be substantially active, and according to Reiners et al. (2007) the  $H_\alpha$ -emission of the primary exceeds that of the secondary by a factor of 7. The same authors find a rotational velocity of about  $v \sin(i) = 10 \text{ km s}^{-1}$  for the primary, while they give only an upper limit of  $5 \text{ km s}^{-1}$  for the secondary. Assuming a magnetic origin of this activity and the same scaling between  $H_\alpha$ -emission and magnetic field strength as found for earlier type stars, Reiners et al. (2007) argue for the presence of magnetic fields of  $Bf \approx 4 \text{ kG}$  for the primary and  $Bf \approx 2 \text{ kG}$  for the secondary.

In this letter we report the discovery of X-ray emission of the eclipsing brown-dwarf binary 2MASS 0535-0546, which provides further support for the presence of magnetic activity in this system.

## 2. Observations and data analysis

2MASS 0535-0546 was serendipitously covered by observations with both the *Chandra* and *XMM-Newton* observatories; the basic properties of these observations are provided in Table 1.

### 2.1. The *Chandra* data

The “flanking field south” of the ONC containing 2MASS 0535-0546 was observed with the “ACIS I” instrument onboard *Chandra*. In the associated image 2MASS 0535-0546 is located relatively far off-axis (6.7 arcmin), but is still well exposed, so that a sensitive search for X-ray emission is feasible. The *Chandra* image in the vicinity of 2MASS 0535-0546 is shown in Fig. 1.

In an effort to suppress background and with the knowledge, that young brown dwarfs have X-ray spectra with median energies of the order of or higher than 1 keV (e.g. Preibisch et al. 2005), we limited the energy range of the image to the 0.5–2.5 keV band; a circle of radius 5 arcsec is drawn around the nominal position of 2MASS 0535-0546. According to our point-spread-function (PSF) modeling the encircled region contains  $\approx 95\%$  of the 1 keV photons from a point source at the respective off-axis position of the target. Within this circle we find a total of 8 photons. Extrapolating the photon numbers measured in the same energy band from nearby source-free regions yields an expectation value of 0.8 background counts. The Poisson probability of obtaining 8 or more counts with an expectation value of 0.8 is only  $2 \times 10^{-7}$ . Therefore, we attribute the recorded signal to an X-ray source with a count level of  $7.2 \pm 2.8$  photons. What about out-of-band photons? In the considered source region not a single photon with an energy below 500 eV was detected, while two photons are contained in the 2.5–10 keV band. This number is, however, in good agreement with the expectation value derived from the close-by comparison region, and we, thus, attribute these photons to background.

The median energy of the source photons is 1.4 keV, a value going well with those obtained by Preibisch et al. (2005) for 8 other brown dwarf members of the ONC detected in a quiescent state. For the depth of the absorbing column towards 2MASS 0535-0546 we estimated a value of  $n_H = 10^{21} \text{ cm}^{-2}$  combining the visual extinction of  $A_V \approx 0.75 \text{ mag}$  given by Stassun et al. (2006) with the relation

$$n_H [\text{cm}^{-2}] = 1.79 \times 10^{21} \text{ mag}^{-1} \cdot A_V$$

derived by Predehl & Schmitt (1995); a result consistent with the lower values derived from brighter, close-by X-ray sources. Assuming an absorbed one-component thermal spectrum with subsolar (0.3) abundances, a plasma temperature of  $\approx 2 \text{ keV}$ , and a distance of 450 pc (e.g. Stassun et al. 2006) we compute an X-ray luminosity of  $(3.0 \pm 1.2) \times 10^{28} \text{ erg/s}$  in the 0.5–2.5 keV band, which – again – is well covered by the range determined by Preibisch et al. (2005).

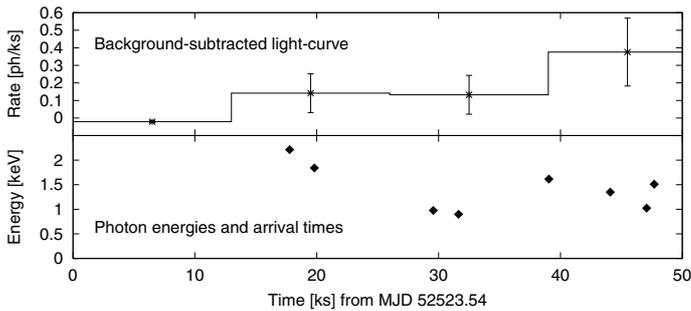
To check the uniqueness of our identification we searched for other potential emitters close (30 arcsec) to 2MASS 0535-0546, but neither Simbad<sup>1</sup>, NED<sup>2</sup>, nor the 2MASS-survey provided any candidates in the environment under consideration. Therefore, we attribute the detected X-ray emission to 2MASS 0535-0546.

#### 2.1.1. Timing

Do the source photons arrive homogeneously distributed in time or not? In Fig. 2 we present the background-subtracted 0.5–2.5 keV band light-curve of 2MASS 0535-0546 in the upper panel and the individual photons (registered by their energies) plotted against arrival time in the lower panel. While no photons arrived during the first quarter of the observation, the assumption of a constant arrival rate is still consistent with the observations. More importantly, the light curve (cf., Fig. 2) suggests the presence of persistent X-ray emission more or less homogeneously distributed in arrival time and not flaring emission as – for example – observed in a number of brown dwarf ONC members (Preibisch et al. 2005) or the ultra cool dwarf LHS 2065 (Schmitt & Liefke 2002).

<sup>1</sup> <http://simbad.u-strasbg.fr/simbad/>

<sup>2</sup> <http://nedwww.ipac.caltech.edu/>



**Fig. 2.** Upper panel: background-subtracted 0.5–2.5 keV band light curve (13 ks binning). Lower panel: photon energy against arrival time.

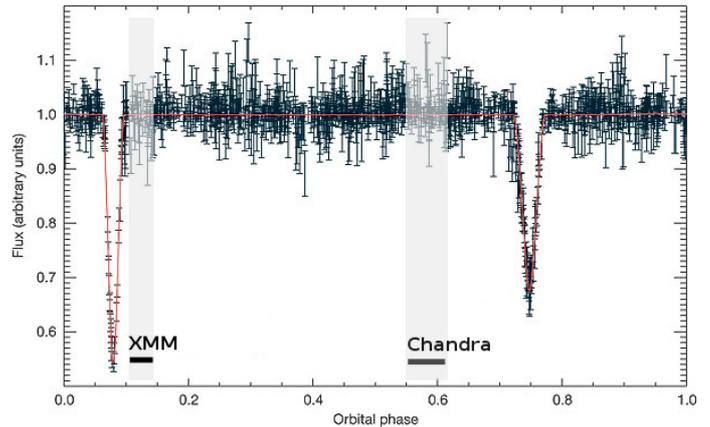
## 2.2. The XMM-Newton data

As 2MASS 0535-0546 is clearly detected in the *Chandra* data, we searched for further evidence in other serendipitous X-ray observations. In an XMM-Newton observation of  $\iota$  Orionis 2MASS 0535-0546 is located roughly 9 arcmin off-axis and we perform a similar analysis as for the *Chandra* data, i.e., we define a source-free background region in the vicinity of 2MASS 0535-0546 and concentrate on the energy range 0.5–2.5 keV. We calculate the excess counts in a circular region with a radius of 15 arcsec (to take into account the larger XMM-Newton PSF) around the nominal source position.

While in the *Chandra* image 2MASS 0535-0546 is clearly separated from all neighboring sources (see Fig. 1), we can unfortunately not exclude some contamination from close-by sources in the XMM-Newton data. Furthermore, in the image constructed from the pn data (i.e., the most sensitive instrument onboard XMM-Newton) the readout strip generated by the out of time events from the central bright source ( $\iota$  Orionis) is located less than one arcmin from 2MASS 0535-0546 providing yet an additional source of possible contamination. Momentarily neglecting these problems, we find  $8 \pm 4$ ,  $7 \pm 4$  and  $13 \pm 6$  excess photons above the background for the MOS 1, MOS 2, and pn, data respectively. Converting into count rates and fluxes using the same model as for the *Chandra* photons (cf. Sect. 2.1) and a vignetting factor of 0.6 (see XMM-Newton-Users Handbook Sect. 3.2.2.2), we find a value of  $(14.0 \pm 4.0) \times 10^{28}$  erg/s for the averaged X-ray luminosity in the MOS 1, MOS 2, and pn data using WebPIMMS<sup>3</sup>. This is a factor of five higher than the X-ray flux from 2MASS 0535-0546 observed with *Chandra*. If we now estimate the contamination level of the source region by placing a similarly sized region at a comparable position with respect to the neighboring, contaminating sources, the observed flux level decreases to values roughly consistent with the *Chandra* measured flux. Although the XMM-Newton data alone are insufficient to claim a detection, we conclude that they are at least consistent with the assumption of X-ray emission from 2MASS 0535-0546 at the same level as observed with *Chandra*, and from an inspection of the arrival times of individual photons we can also exclude the presence of (stronger) flares.

## 2.3. Phase coverage of X-ray observations

In Fig. 3 we show the phase folded optical light curve of 2MASS 0535-0546 as given by Stassun et al. (2006), where we indicate those phase intervals covered either by XMM-Newton or *Chandra*. The XMM-Newton observation



**Fig. 3.** Phase folded photometric data from Stassun et al. (2006). Observation phases of *Chandra* and XMM-Newton are indicated by black bars at the bottom and a gray column.

takes place shortly after the eclipse of the secondary, but unfortunately, none of the eclipses is covered by the presently available X-ray data. Therefore, we are unable to unambiguously attribute the detected X-ray emission to any of the individual components of 2MASS 0535-0546, which is clearly a task for follow-up observations.

## 2.4. Chromospheric and coronal activity

The bolometric luminosity,  $L_{\text{bol}}$ , of the individual components can be calculated from

$$L_{\text{bol}} = 4\pi r^2 \sigma T^4, \quad (1)$$

with  $r$  denoting the radius of the brown dwarf,  $\sigma$  the Stefan-Boltzmann constant, and  $T$  the effective temperature. Using the values given by Stassun et al. (2007) for the radii and temperatures of 2700 K and 2800 K, we find bolometric luminosities of  $8 \times 10^{31}$  erg/s and  $5.1 \times 10^{31}$  erg/s for the primary and secondary component.

As the primary shows strong magnetic activity (Reiners et al. 2007), we naturally blame it to be also responsible for the X-ray emission. Comparing the X-ray luminosity of  $3 \times 10^{28}$  erg/s to its bolometric luminosity leads to a ratio of  $\log L_X/L_{\text{bol}} = -3.4$ , and similar results of  $-3.2$  and  $-3.6$  are obtained if not the primary but the secondary or both were the X-ray bright component(s).

Preibisch et al. (2005) detected quiescent emission from 8 young brown dwarfs in the ONC. We find that both the X-ray luminosity of 2MASS 0535-0546 and the  $\log L_X/L_{\text{bol}}$ -ratio (no matter whether the primary or the secondary is held responsible for the X-ray emission) point to a rather active, however, not unprecedented object. From the activity point of view, it appears similar to the late M dwarf 2MASS J05350705-0525005 (COUP 280), which is the most active brown dwarf in the (quiescent) Preibisch et al. (2005) sample showing an  $\log L_X/L_{\text{bol}}$ -ratio of  $-3.3$ ; with an X-ray luminosity of  $5 \times 10^{28}$  erg/s it is also among the most luminous. This provides further support for our attribution of the recorded X-ray flux to the 2MASS 0535-0546 system.

What do these outcomes imply for the relation between chromospheric and coronal activity in 2MASS 0535-0546? Reiners et al. (2007) derive values of  $\log(L_{\text{H}\alpha}/L_{\text{bol}}) = -3.5$  for the primary and  $\log(L_{\text{H}\alpha}/L_{\text{bol}}) = -4.3$  for the secondary. Substituting our results we obtain  $\log(L_X/L_{\text{H}\alpha}) = 0.1$  if the primary were the X-ray bright constituent and  $\log(L_X/L_{\text{H}\alpha}) = 0.7$  if it is the secondary.

<sup>3</sup> <http://heasarc.nasa.gov/Tools/w3pimms.html>

These values compare well to those given by [Dahm et al. \(2007\)](#) for similarly young low-mass ( $M < 0.5 M_{\odot}$ ) classical and weak-line T-Tauri stars in NGC 2264, and are also within the range of  $\log(L_X/L_{H\alpha})$ -ratios obtained by [Hawley et al. \(1996\)](#) for active cluster and field M-dwarfs in a more advanced evolutionary state.

### 3. Summary and conclusions

In summary, we find an unambiguous X-ray detection of the eclipsing brown-dwarf binary 2MASS 0535-0546. An X-ray source at the nominal position of 2MASS 0535-0546 is clearly seen with the *Chandra* observatory, and the results are also compatible with an XMM-Newton image observed about one year earlier. The X-ray luminosity of 2MASS 0535-0546 is of the order of  $3 \times 10^{28}$  erg/s, and even though the *Chandra* light curve might indicate some moderate increase in luminosity, no flaring activity is seen in either of the observations. Therefore, we attribute the flux to quiescent X-ray emission.

An inspection of the source photons recorded by *Chandra* shows that the observed plasma emits at a temperature of at least 1 keV and probably more. The relative hardness of the spectrum is compatible with the results obtained by [Stelzer & Micela \(2007\)](#) for a wide and similarly young brown-dwarf binary system. From the bolometric luminosity of the primary component we compute a value of  $-3.4$  for the  $\log(L_X/L_{\text{bol}})$ -ratio, which is close to the saturation limit of  $\approx -3$  and within the range of values determined by [Preibisch et al. \(2005\)](#) for other brown dwarf members of the ONC detected in quiescence as well as compatible with values computed by [Stelzer et al. \(2006\)](#) for other young brown dwarfs. Invoking the findings of [Reiners et al. \(2007\)](#) we find  $\log(L_X/L_{H\alpha})$  values well consistent with previously published results for low-mass stars. Unfortunately, none of the optical eclipses is covered by the available X-ray data, so we have no way at the moment to assign the X-ray flux to the individual components of 2MASS 0535-0546.

What can our results tell us about the origin of the temperature reversal? The effect may be caused either by a non-coeval formation of the brown dwarfs or by the impact of magnetic fields, which hamper energy transport by convection. The X-ray detection of 2MASS 0535-0546 alone supports the presence of magnetic fields causing the X-ray emission; further evidence is the hardness of the source photons indicating that magnetic processes are the source of the activity. Our results are, therefore, fully in line with those of [Reiners et al. \(2007\)](#), pointing towards the presence of strong magnetic activity in 2MASS 0535-0546 near the saturation limit and hence a magnetic origin of the observed temperature reversal.

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