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X-ray emission probing the limiting cases of stellar dynamos

B. Stelzer[1,2]

[1] Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, Piazza del Parlamento 1, I-90134 Palermo e-mail: stelzer@astropa.unipa.it

[2] INAF - Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo

Abstract. Magnetic activity, driven by a dynamo, is a frequently observed phenomenon on solar-like stars and the Sun itself. Its manifestations include chromospheric and coronal emission. Solar-like stars regenerate and accumulate their magnetic fields in the transition zone between the radiative core and the convective envelope. Consequently, stars in which this 'overshoot' region is absent are not expected to display activity. In particular, the critical cases are (A) the fully radiative intermediate-mass stars ($M \geq 2M_{\odot}$), and (B) the fully convective lowest mass stars ($M \leq 0.3M_{\odot}$) and brown dwarfs. Nevertheless, high-energy emission is observed from both classes of objects. I discuss recent efforts to constrain the emission mechanism in these limiting regimes of the stellar dynamo by means of X-ray observations with the *Chandra* satellite.

Key words. X-rays – intermediate-mass stars – brown dwarfs

1. Introduction

Late-type stars have long been known to display signatures of magnetic activity evidencing solar-like dynamo action (Rosner et al. 1985). According to models the solar $\alpha\Omega$-dynamo resides in the overshoot region connecting the radiative core and the convective envelope. Consequently, this mechanism is expected to break down in stars with interior structure different from that of the Sun. The limiting cases concern two regimes of stars: (A) stars with intermediate-mass, which lack a convective envelope, and (B) very low-mass stars, which are fully convective. The latter group includes the brown dwarfs (BDs), as there is no qualitative change in interior structure across the substellar boundary.

X-ray emission is an efficient activity indicator, probing the effects of magnetic processes in the outermost and hottest part of the atmosphere, the corona. For stars of intermediate mass (spectral types late B and early A), due to the absence of a convective zone, no magnetic activity is expected. Therefore, their X-ray detection which has repeatedly been reported throughout the literature (e.g. Stelzer et al. 2003,and references therein) has remained a mystery to date. The observed emission is commonly attributed to unresolved late-type companions. But previous X-ray and IR observations did not have the spatial resolution

Send offprint requests to: B. Stelzer
Correspondence to: Piazza del Parlamento 1, 90134 Palermo

to identify these objects near the bright primaries.

At the bottom end of the main-sequence (MS) the $\alpha\Omega$-dynamo may be replaced by alternative field generating mechanisms, e.g. an α^2-dynamo (Rädler et al. 1990) or a turbulent dynamo (Durney et al. 1993). But their effects on the emitted radiation are difficult to predict. Beyond spectral type M6 the X-ray regime is widely unexplored due to a lack of sensitive and systematic observations. With the exception of the M8 star vB 10 (Fleming et al. 2003) all X-ray detections of M dwarfs cooler than spectral type M7 are ascribed to flares, i.e. outbursts on a time-scale of hours that arise from reconnection of magnetic field lines. It is unclear to date whether ultra-cool dwarfs can sustain persistent X-ray emission, as is typically observed on higher-mass stars. In particular, such a 'quiescent' corona could not be established for any BD so far.

In this contribution I examine the efficiency of magnetic activity, as probed by X-ray emission, in the limiting cases of stellar dynamos introduced above.

2. X-ray emission from the BD binary Gl 569 Bab

Gl 569 B is a low-mass companion to the nearby (9.8 pc; Dahn et al. 2002) dM2e star Gl 569. Martín et al. (2000) found that the companion itself is a binary of 0.1″ separation. The dynamical masses of Gl 569 Ba and Gl 569 Bb were derived by Zapatero Osorio et al. (2004) from a combination of radial velocity measurements and astrometry, yielding 99 % confidence intervals of $M_{\rm Ba} = 0.055 - 0.087\,M_\odot$ and $M_{\rm Bb} = 0.034 - 0.070\,M_\odot$. The lower-mass component is thus the first object confirmed as substellar independent of models.

The Gl 569 B pair is confirmed to be bound to the flare star Gl 569 A both spectroscopically and by proper motion (Forrest, Skrutskie, & Shure 1988; Lane et al. 2001). Its companion character is an important factor, because it provides knowledge on the age of the BD pair through the age of the primary star. Therefore, one of the crucial parameters that presumably influences stellar activity is fixed.

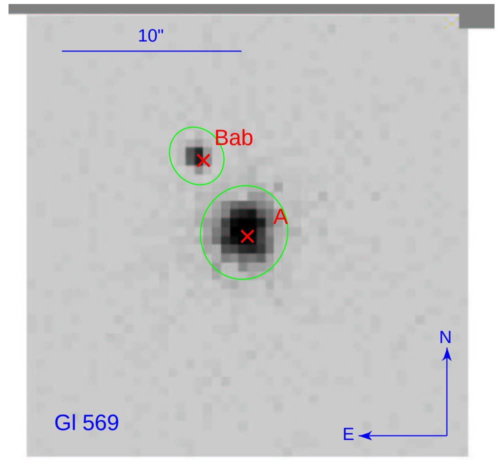

Fig. 1. *Chandra* ACIS-S image of the Gl 569 system. The size of the image is 50 × 50 pixels. X-points denote the optical/IR position of Gl 569 A and Gl 569 Bab. Ellipses mark the corresponding X-ray sources.

The Gl 569 system was observed in June 2004 with the Advanced CCD Imaging Spectrometer (ACIS) onboard *Chandra*, using the S3 chip in imaging mode for a total exposure time of 25 ks; see Stelzer (2004). Two X-ray sources are found which are unambiguously identified with Gl 569 A and Gl 569 Bab, respectively, shown in Fig. 1. The angular separation and the position angle of the two X-ray sources are in good agreement with those published by Lane et al. (2001) based on near-IR images.

A total of 250 source counts were collected for Gl 569 Bab. Its X-ray lightcurve is shown in Fig. 2. The beginning of the observation is dominated by a strong flare on the BD binary, with ~ 93 % of all source photons being concentrated in the first 12 ks of the observation. In the remainder of the observing time a total of 23 photons were collected in the source area, of which about 6 are expected to be background events, mostly contaminants from Gl 569 A. Assuming a 1-T plasma without absorption yields an X-ray luminosity of $\log L_{\rm Q} = 25.8$ erg/s during the quiescent phase and of $\log L_{\rm F} = 27.5$ erg/s in the flare peak.

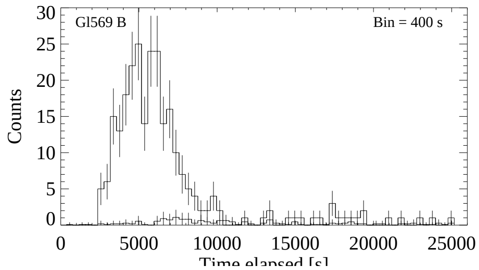

Fig. 2. Source and background lightcurves of Gl 569 Bab.

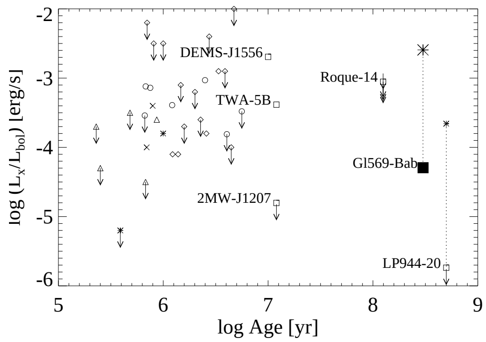

Fig. 3. Ratio of $L_{\rm x}/L_{\rm bol}$ versus age for BDs: *triangles, diamonds, open circles* – bona-fide BDs in three different star forming regions (spectral types ≥ M7) with a random one order of magnitude spread in age. The remaining objects are labeled by their names. Flaring BDs are displayed as an asterisk, and those with accretion signatures in the Hα profile as x-points. For references to the individual data points see Stelzer (2004).

Evaluating the ratio between X-ray and bolometric luminosity for the two components in the BD binary using the bolometric luminosities given by Gorlova et al. (2003) yields $\log{(L_{\rm x}/L_{\rm bol})_{\rm Q}} \sim -4.3$ and $\log{(L_{\rm x}/L_{\rm bol})_{\rm F}} \sim -2.6$, while the average is $\log{(L_{\rm x}/L_{\rm bol})} \sim -3.3$. Gl 569 Bab thus adds to only a handful of late-M type objects that have shown flares, with emission levels near or above the canonical 'saturation level' of $L_{\rm x}/L_{\rm bol} \sim 10^{-3}$. The detection of quiescent emission from Gl 569 Bab means that the sharp decline in the quiescent coronal activity for ultra-cool dwarfs conjectured by Fleming et al. (2003) must be questioned.

With its estimated age of 300 – 800 Myr Gl 569 Bab constitutes an important link between activity in star forming regions, associations, and open clusters, and the more evolved field stars and BDs. Fig. 3 puts the *Chandra* observation of Gl 569 Bab in context with observations of younger BDs, and the only previous X-ray detection of an evolved field BD, LP 944-20 (Rutledge et al. 2000).

A factor of 4 – 5 more photons have been collected for Gl 569 Bab with respect to all other late-M dwarfs, allowing for the first time a meaningful spectral analysis of such an object. A statistically acceptable interpretation of the X-ray spectrum in terms of thermal emission requires a two-temperature model with significant emission above 1 keV, but a similarly strong cool component of ∼ 3.2 MK. Low coronal temperatures seem to be characteristic for all but the youngest BDs. This is all the more remarkable as temperatures are known to rise in stellar flares. The *flare temperatures of the evolved BDs* (Gl 569 Bab and LP 944-20) are similar to the *quiescent temperature of the middle-aged BD* TWA-5B on the one hand and to the *quiescent temperature of the evolved star* vB 10 on the other hand.

3. X-ray emission from intermediate-mass stars

Identifying cool companion stars to early-type stars and certifying whether they are the cause for the observed X-ray emission calls for a complex observational approach involving high spatial resolution imaging observations and spectroscopy in different wavelength bands. Bound late-type companions to early-type MS stars are expected to be young, because of the different evolutionary time-scales of early- and late-type stars. And, since late-type pre-MS stars are ubiquitous X-ray sources, the hypothesized companions are plausible candidates for X-ray emitters.

Our strategy to test the companion hypothesis is as follows: (i) search for cool companions to A and B stars with high-resolution

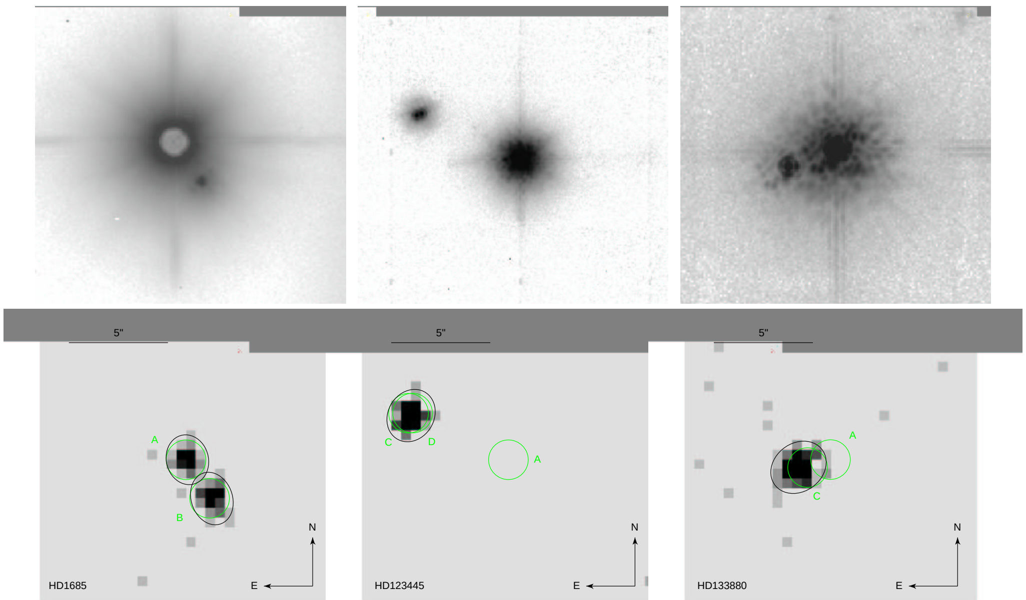

Fig. 4. IR and X-ray images of late-B stars: *top* - Adaptive optics *K* band images obtained with ADONIS at the 3.6m ESO telescope showing newly discovered faint IR objects at separations of 1.2...5.6″ from the B-type primary (see Hubrig et al. 2001 and Huélamo et al. 2001); *bottom* - The same systems resolved with *Chandra* (Stelzer et al. 2003).

imaging observations in the IR using adaptive optics (AO), (ii) follow-up X-ray observations with similarly high spatial resolution to pinpoint the X-ray emitter in the newly identified systems, (iii) IR spectroscopy for those intermediate-mass stars that are X-ray detected even after being resolved from any (sub-)arcsecond visual companions to search for signatures of even closer companions.

In this article I will focus on *Chandra* X-ray observations of late-B stars for which the recent AO studies of Hubrig et al. (2001) and Huélamo et al. (2001) have identified AO 'companions'. It should be kept in mind, however, that the objects newly discovered in AO imaging – termed companions henceforth – have not been confirmed yet to be physically bound to the 'primaries'.

Chandra is the first and so far only X-ray satellite providing spatial resolution comparable with AO observations. Within this project 9 late-B stars on the MS were observed with *Chandra*'s ACIS. The targets have shown to be X-ray emitters in the *ROSAT* All-Sky Survey (= RASS; Berghöfer et al. 1996) and they have AO companions with separations ranging from $\sim 1 - 8''$, i.e. the systems are well resolvable with *Chandra*. This sample is complemented by data of two stars extracted from the *Chandra* archive, that obey the same criteria: spectral type late-B, on the MS, X-ray sources according to the RASS, and close companions resolvable with *Chandra*.

In addition I scanned the *Chandra* archive for any observations of HAeBe stars, and found 15 of them. It should be pointed out that the HAeBe star sample diverges from the original selection criterion, in that many of them are not known to have close visual companions. But they are of interest to our study because the physical processes related with their X-ray emission may be different from those of the

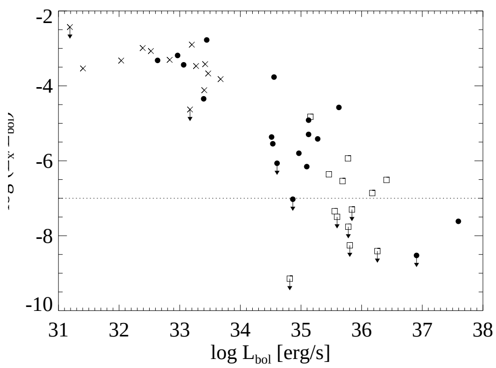

Fig. 5. Ratio between X-ray and bolometric luminosity for *Chandra* observed A and B stars; *squares* - B stars on the MS, *crosses* - AO discovered companions to MS B stars, and *circles* - HAeBe stars and their cooler companions. The dotted line indicates the empirical L_x/L_{bol} ratio for wind-driven stellar X-ray sources.

more evolved MS B/A-type stars. A comparison between X-ray properties of HAeBe and MS B/A-type stars should allow to test whether and where there is an age-related transition or shut-off in the dynamo action.

Some examples for the AO and *Chandra* imaging are given in Fig. 4. To summarize, almost all of the new IR sources turn out to be X-ray emitters (see discussion in Stelzer et al. 2003, where the first 5 targets have been presented). However, this does not prove the companion hypothesis, as we have detected also 7 out of 11 MS B stars. One of them is known to be a spectroscopic binary, the other 6 B stars remain candidates for being intrinsic emitters until tested for closer companions with IR spectroscopy. Among the HAeBe stars 12 out of 15 are detected with *Chandra*.

Fig. 5 displays the L_x/L_{bol} ratio for all components of the A and B stars observed so far with *Chandra*. In such a diagram, in general, the most active late-type stars are observed to display values near 10^{-3}. Less active late-type stars range between $L_x/L_{bol} = 10^{-4...-5}$. O and early-B stars, for which X-ray emission is thought to arise in a stellar wind, are clearly distinct from late-type stars with a typical value of $L_x/L_{bol} \approx 10^{-7}$ (Berghöfer et al. 1997). In the sample examined here the IR-discovered companions display $\log(L_x/L_{bol})$ values near the saturation limit of 10^{-3}. For all undetected intermediate-mass MS stars of the sample the upper limits we derive are lower than the canonical value of 10^{-7}, making stellar winds an unlikely cause for their production. The detected MS B stars show intermediate values of $\log(L_x/L_{bol})$ and need to be examined for the presence of further, as yet undiscovered companions. The HAeBe stars fill the gap in L_{bol} between the intermediate-mass stars and their low-mass companions. In terms of $\log(L_x/L_{bol})$ they also occupy an intermediate position with values of $-4... -6$, except for the two very luminous objects MWC 297 and HD 147889. However, we note that the bolometric luminosities of the HAeBe stars in some cases are highly uncertain, due to excess emission from remnant circumstellar material.

4. Discussion and Summary

IR and X-ray observations of intermediate-mass stars allow to examine whether late-type companion stars are the cause of their unexplained X-ray emission. The exceptional spatial resolution of *Chandra* ($\sim 1''$) enables to access in the X-ray range many of the faint IR objects discovered near B stars in recent AO surveys. *Chandra* observations suggest that most new, faint IR objects are truely bound companions. The detection of ~ 60 % of the MS B-type primaries with *Chandra* indicates the need to search for even closer, spectroscopic companions. The age dependence of dynamo action in intermediate-mass stars is studied by a comparison of X-ray properties of the primaries in our sample of MS stars to the X-ray properties of HAeBe stars. We find that the detection fraction with *Chandra* is even higher for the latter ones (~ 80 %). This may be due to either of two reasons: (i) a shut-off of the magnetic dynamo at a critical as yet undefined point in the life of a B-/A-type star, or (ii) unidentified binary companions of HAeBe stars.

X-ray emission has lately been revealed from a substantial number of BDs in various star forming regions and young associations (see Fig. 3). But only one evolved BD in the field had been detected in X-rays so far. BDs are not able to fuse hydrogen and subsequently must cool down and become fainter as they age. Therefore, their detection at young ages but non-detection in more evolved stages could be due to: (A) a decline of L_x with age, as expected if the L_x/L_{bol} correlation typical for the higher-mass late-type stars holds also in the sub-stellar regime; (B) an atmospheric temperature too low to provide enough coupling between matter and magnetic field leading to a shut off of the dynamo (Mohanty et al. 2002). The detection of a strong X-ray flare and quiescent emission on a comparatively evolved BD demonstrates that coronae of VLM objects can remain powerful beyond the youngest ages. Gl 569 Bab is one of only two ultra-cool dwarfs older than $\sim$ 100 Myr detected in X-rays. Indeed, most previous observations of late-M dwarfs were not sensitive enough to sample the range of L_x/L_{bol} values expected by extrapolation from the early-M dwarfs.

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