Mem. S.A.It. Vol. 76, 271

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A glimpse on the results of the Chandra Orion Ultradeep Project (COUP)

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Abstract. In January 2003 an exceptionally deep *Chandra* ACIS observation of the Orion Nebula Cluster and of the embedded populations around OMC-1 has been performed. This observation has been nicknamed the *Chandra* Orion Ultradeep Project (COUP). The project is being pursued by a large international team lead by E. Feigelson. We briefly summarize some of the results obtained so far from the ongoing analysis of the data and their impact on our understanding of the star formation process and the role played by high-energy radiation.

Key words. Star Formation – X-rays; COUP – Orion

1. Introduction

X-ray observations of star-forming regions have established young stars as bright, up to 4 dex higher than the Sun, X-ray sources, from the Class I stage, where an accreting envelope is still present, to the Class III (or WTTS) stage, where very little circumstellar disk remains and the star's photosphere is hardly distinguishable from that of more mature stars (cf. Feigelson & Montmerle 1999). Still after more than two decades from the first *Einstein* X-ray observations we have not found yet a definitive answer to very basic questions: Is the young stellar objects (YSO) X-ray emission *always* a scaled up version of solar one? Can we distinguish between star-disk interactions and "pure" solar-like coronal activity? What is the interplay between accretion and X-ray emission in young stellar objects (see Favata's paper in this volume)?

The realm of these very basic questions has been recently enlarged by an additional one, namely: What is the effects of X-rays on the large scale evolution of molecular cloud as well on the evolution of circumstellar disks and planetary systems?

In order to answer these crucial questions we need top quality data taken at many wavelengths, including X-rays, taken toward key star formation regions, such as Orion, ρ Oph, Taurus, etc. COUP is one of the required steps to start answering some of the key questions on star formation and related phenomena.

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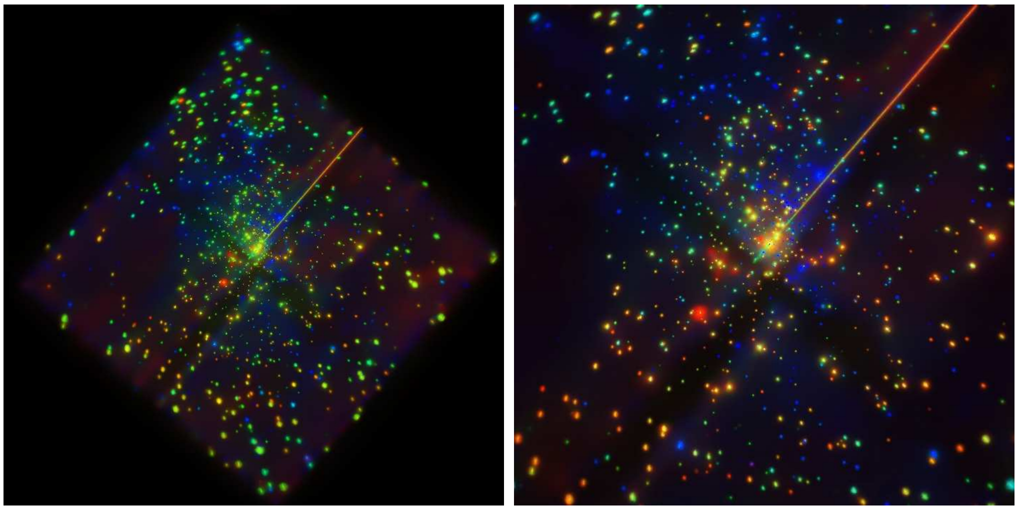

Fig. 1. A RGB false color representation of COUP data. (left) The image of the entire ~ 17 x 17 sq. arcmin surveyed area. The energy of collected photons has been color coded as follows: 0.2-1.0 keV in red, 1.0-2.0 keV in green, 2.0-8.0 keV in blue. The luminous line starting at the image center is due to "out-of-time" events associated to an extremely intense source that, lacking a shutter, are collected during the CCD read-out cycles. (right) The RGB image of the central part of the surveyed area.

2. The Orion Nebula Cluster and COUP

The Orion Nebula Cluster (ONC) is likely the best studied group of PMS stars in the Galaxy. Recent ONC studies (cf. Hillenbrand 1997; Hillenbrand & Carpenter 2000) have found more than 2000 members with masses ranging from O-type stars down to the brown dwarf (BD) ones. More recent studies based on deep VLT infrared images (McCaughrean et al. 2005) are further enlarging the sample of known ONC very-low mass members.

The *Chandra* Orion Ultradeep Project (COUP), a unique 10 day (850 ksec) long, nearly continuous observation of the Orion Nebula Cluster and of the OMC-1 cloud, provides the most comprehensive dataset ever acquired on the X-ray emission of pre-main sequence stars. The project is lead by E. Feigelson and sees the involvement of more than 30 scientists from USA, Europe and Asia. The quality of the collected data is illustrated by the false color images in Fig. 1.

The project has started at the time of the Chandra AO-4 when E. Feigelson asked a team of ~ 30 scientists to join a proposal for a very deep *Chandra* observation of Orion and to start, in case of success, a large collaborative effort. S. Murray, the Chandra HRC PI, and G. Garmire, the Chandra ACIS PI, decided to contribute to this enterprise with 100 and 50 ksec of their guaranteed time, respectively; the other 700 ksec have been granted by the *Chandra* TAC as part of the Large Program budget. In January 2003 the observations have been performed and soon there after the data have been released to the PI and his team.

3. COUP Science Results

The project is in a very advanced stage and the considerable task of performing a very homogeneous analysis of the data has been already accomplished (Getman et al. 2005). A total of 1616 X-ray sources have been detected by the combined use of the Pwdetect (developed at INAF-OAPA) and of the Wavdetect (devel-

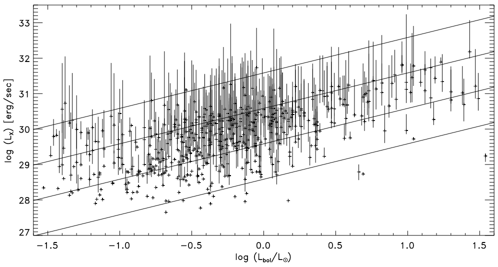

Fig. 2. A summary plot of the Bayesian block time analysis; the bars define the range of observed $L_{X,min}$ and $L_{X,max}$ for each source. The upper and lower lines mark the log L_X/L_{BOL} -5 and -2 locus, respectively (adapted from Preibisch et al. 2004a).

oped at CXC/SAO) algorithms. For most of the X-ray sources ample multi-wavelenght information is available thanks to already published or newly obtained data. As matter of fact, since the first months of 2004, a large database of information is available to the COUP collaboration and has been the subject of many scientific analyses. In the following, on behalf of the COUP team, we will briefly present some of the scientific results that have been recently obtained.

3.1. X-ray Variability

One way to characterize the variability is to subdivide the X-ray light curve in segments within which source intensity can be considered constant. The COUP team has adopted two different segmentation methods: the first based on a Bayesian block (BB) approach (Scargle 1998), the second on a maximum likelihood block (MLB) approach. This latter has been developed by E. Flaccomio at INAF-OAPA to purposely overcome some limitations of the BB method for the kind of investigation we had in mind. In particular, the MLB methods allows in a very simple way to asses the source characteristic "quiescent" intensity (more details are provided by Wolk et al. 2004).

As summarized in Fig. 2, and confirmed by a rigorous statistical analysis, essentially all COUP sources are X-ray variable. We see flares (cf. Wolk et al. 2004; Favata et al. 2004), long-term, quite enigmatic to explain, variations and for the first time evidence of rotational modulation (cf. Fig. 3) in the X-ray emission of tens YSOs emitting at, or near, the saturated level, $\log L_X/L_{BOL} = -3$ (Flaccomio et al. 2004). This latter finding, in particular, implies that the coronae of few million year old PMS stars are highly inhomogeneous and that the saturation can hardly be explained by a full coverage of PMS stellar surface by active regions.

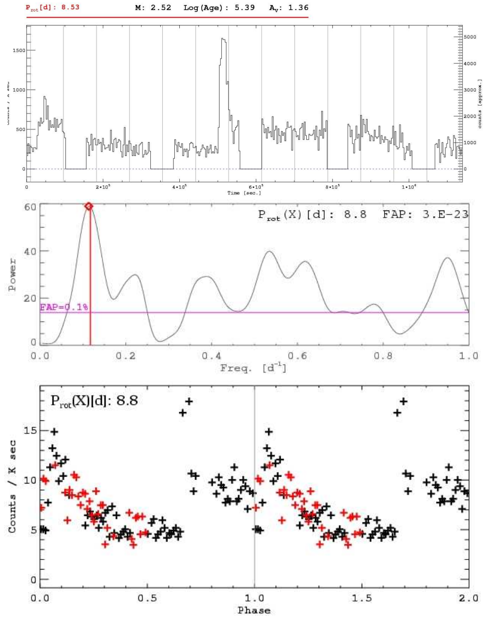

Fig. 3. (top) X-ray light curve of one of the ONC member. The observation spans over about 12 days. The upper-left horizontal segment represents the value of the optically derived period of 8.52 days. (center) The periodogram derived from the analysis of the above light curve showing the peak associated with the X-ray derived period. (bottom) The COUP data folded with the X-ray derived period of 8.8 days. The different colors (visible in the electronic version) refer to the two distinct periods covered by the observation (adapted from Flaccomio et al. 2004).

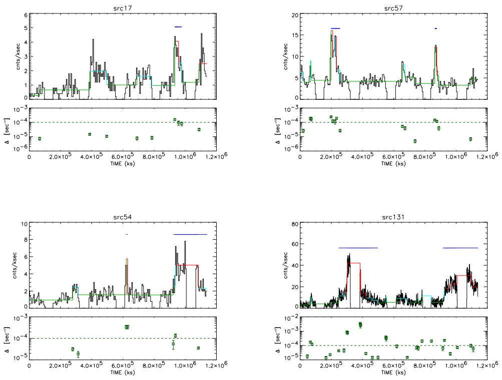

Fig. 4. For each of the four plots, the upper panel shown examples of COUP light-curves of solar mass stars. Binning is done on different time ranges between 1ks and 10ks depending on the count rate. The horizontal segments within the light-curve indicate blocks of constant rate. The line colors (green, cyan and red visible in the electronic version) indicate the characteristic, elevated and flare time periods, respectively. Block breaks occur at the 95% confidence level. The (blue) segment above lightcurve indicate the duration of each detected flare. The lower panels show 1/Rate*(dRate/dTime) between two adjacent blocks;, the normalized derivative criterion is adopted to identify a flare (adapted from Wolk et al. 2004).

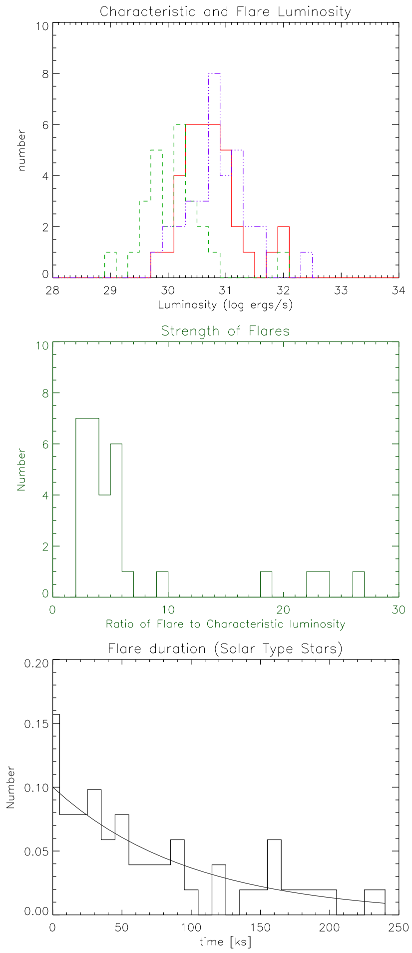

Fig. 5. (top) Distributions of characteristic (short-dashed green), flare average (continuous red), and flare peak (short-long dashed blue) X-ray luminosities. (center) Distribution of the ratio of flare average and characteristic X-ray luminosities. (bottom) Distribution of flare duration times (adapted from Wolk et al. 2004).

3.2. X-ray Variability of Solar Mass PMS Stars

Given the size of the ONC sample it is possible to study the characteristics of X-ray variability in selected ranges of masses. Wolk et al. (2004) have conducted a detailed analysis of variability and flare statistic in the sample of the 30 ONC members with $0.9 < M/M_{\odot} < 1.2$ and not affected by strong extinction. One of the aim of this study is to constrain the physical condition in the surrounding of a few million year old solar mass star that is much more active than the present day Sun. A sample of the available data is shown in Fig. 4.

In summary, Wolk and collaborators have found that i) the ONC solar mass PMS stars spend 75% of their time at the "characteristic" level; ii) the flare X-ray luminosity of ONC stars is 10^{2-4} that of present day Sun during a strong flare (this latter being about 10^{28} erg/sec); iii) flares have typically duration from few tens of ksec up to 250 ks and average intensities 3-5 times the characteristic level, but even up to 30 times that level. However there is also evidence of more exceptional flares, such as the one seen on GMR-A, a likely K5 WTT

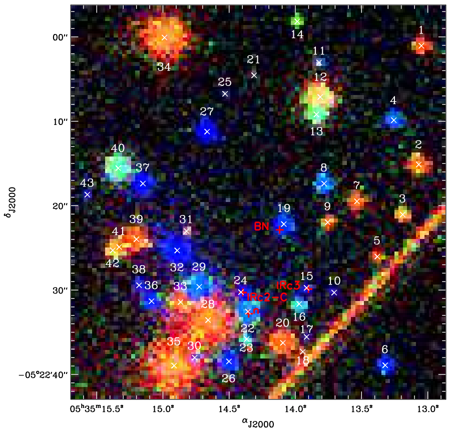

Fig. 6. The COUP image of the BN/KL region showing 43 X-ray sources 18 of which have been detected for the first time. The sources in blue are those seen through an hydrogen column with $\log N_H > 22.2$ and are likely associated with embedded YSO (adapted from Grosso et al. 2004).

star, with a flare peak X-ray luminosity of 10^{33} erg/sec and duration of ~ 5 days (Bower et al. 2003). While the "typical" flares do not seem to be intense enough to significantly affects the circumstellar disk evolution, the more intence ones can play such a role.

3.3. Embedded sources in OMC-1

The COUP data are also allowing to investigate the properties of the population of X-ray sources in the highly obscured BN/KL region hosting several infrared sources associated to YSOs. A total of 43 X-ray sources have been found (cf. Fig. 6) half of which are associated with deeply absorbed and/or embedded sources. The histogram of hydrogen column density derived by the fit to X-ray spectra (cf. Fig. 7) shows that the most extincted/embedded X-ray sources have not known counterparts.

Some of the sources, as the one in Fig. 8, show clear evidence of intense flare-like X-ray variability, posing the question whether the observed variability is associated to "normal" flares, as those seen in late-type stars, or if, instead, we are seeing traces of star-disk interaction and specifically of magnetic reconnection phenomena. This is a subject of a specific investigation briefly summarized below.

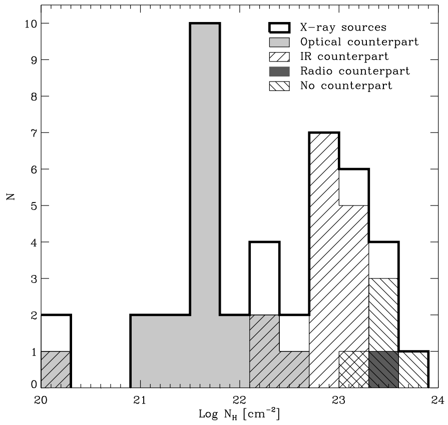

Fig. 7. The histogram of N_H values as derived from fits of X-ray spectra of the COUP sources in the BN/KL region. Extremely large value of N_H are derived for sources without (yet) known counterparts (adapted from Grosso et al. 2004).

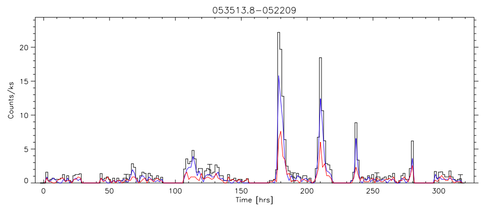

Fig. 8. The light curve of a COUP source in the BN/KL region. Source has $\log N_N = 22.2$ and its counterpart is an IR source with K = 12.2 (adapted from Grosso et al. 2004).

3.4. Evidence of star-disk interaction from the study of intense flares

The analysis of the most intense flares seen in the COUP sources (Favata et al. 2004) performed taking into account the "natural"' decay of emission as well as the presence of sustained heating during the flare as described by Reale & Micela (1998) has shown that in seizable fraction of cases $L \gg R_*$, where L, is the length of the flaring magnetic arch and

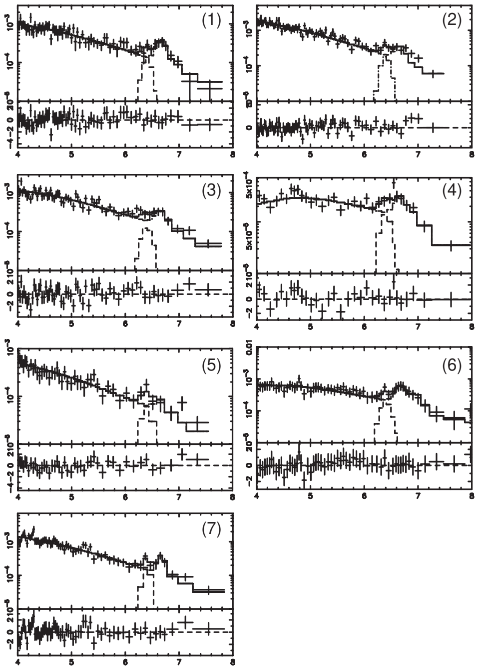

Fig. 9. Spectra and best-fit models of the seven source with a 6.4 keV Fe fluorescent line. The upper panel show the spectra (pluses) and the best-fit models (solid steps) with a 6.4 keV Gaussian component shown as dashed steps. Spectra cover the 4.0-8.0 keV energy range shown along the horizontal axis. The vertical axis shows the intensity in unit of cnt s^{-1} keV^{-1}. The lower panels show the fit residual in unit of χ^2 (adapted from Tusijmoto et al. 2004).

R_* the stellar radius. As the majority of ONC stars are surrounded by disks, it is natural to speculate that the large magnetically confined flaring structures are actually the same type of structures which channel the plasma in the magnetospheric accretion scenario. This is a hint on the long time sought evidence of magnetic structure connecting the YSO upper atmosphere and its circumstellar disk.

3.5. X-ray fluorescence in YSO accretion disks

For 134 out of the 1616 COUP sources we have collected spectra of sufficient quality to allow investigating the characteristic of the spectra in vicinity of the Fe XXV 6.7 keV line looking for the presence of the ~ 6.4 keV neutral Fe line. Such a line is tracer of fluorescent emission from neutral matter and its presence has been found by Imanishi et al. (2001) in the Class I source YLW 16 in ρ Oph. In seven COUP sources the 6.4 keV line has been found (Tusijmoto et al. 2004) and the emission has been interpreted as originating from the circumstellar disk matter illuminated from the X-ray emitted from the PMS stars during intense flares. Additional details and discussion on this, and related, findings can be found in Favata (2005, this volume).

3.6. X-ray luminosity versus mass and rotation

The very sensitive COUP data allows to investigate the existence of a relation between L_X/L_{BOL} and stellar mass and rotation down to X-ray luminosity level never explored in previous studies (Preibisch et al. 2004a). As shown in Fig. 10 the ONC pre-main sequence stars have log L_X/L_{BOL} whose average value is about -3 and whose minimum value drastically decreases for masses greater than $3M_{dot}3$ and decrease more slowly for masses below $1M_\odot$. Fig. 11 shows that no relation exist between L_X/L_{BOL} and stellar rotation for pre-main sequence stars, confirming previous findings (Feigelson et al. 2003; Flaccomio et al. 2003). COUP data seem to suggest also a possible decrease of L_X/L_{BOL} for very fast rotating PMS stars.

3.7. X-ray luminosity of brown dwarfs

Taking advantage of the sensitivity of the COUP images and of the availability (cf. Fig. 12) of 34 spectroscopic confirmed BDs in ONC (Slesnick et al. 2004) it has been possible to investigate the X-ray emission level

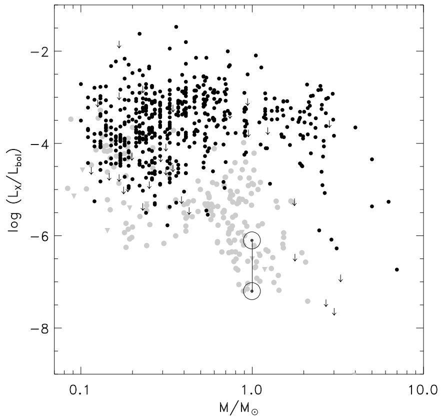

Fig. 10. Scatter plot of L_X/L_{BOL} vs. stellar mass. Black symbols refer to the ONC members, while the gray symbols refer to nearby stars studied with ROSAT. The two circles joined with a vertical segments indicates the range of data for the Sun (adapted from Preibisch et al. 2004a).

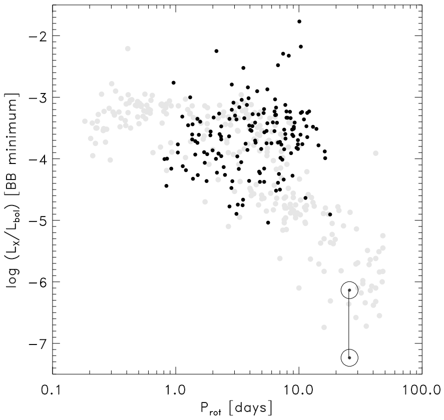

Fig. 11. Scatter plot of L_X/L_{BOL} vs. stellar period. Black symbols refer to the ONC members, while the gray symbols refer to nearby stars studied with ROSAT. The two circles joined with a vertical segments indicates the range of data for the Sun (adapted from Preibisch et al. 2004a).

of young BDs (Preibisch et al. 2004b). We have detected 9 out of the 34 BDs investigated (cf. Fig. 13), all of them are variable and a two of them have been detected only because they flare. The remaining 7 would have been detected even outside the flares. The average X-ray luminosity of young BDs as a class is quite low and seem to follow the decrease of L_X/L_{BOL} with decreasing mass found for the ONC PMS stars. Sometimes individual BDs can be detected because of flares during which the X-ray luminosity is 10-100 times higher (at least) than the "quiescent" level. It is noteworthy that a longer exposure increases the chance to find the BDs that behave like "intermittent" X-ray sources.

4. Summary and Conclusions

We have presented some of the results from the ongoing analysis and interpretation of the very rich and unique COUP dataset. Many analyses have been already concluded and a very large fraction has been finalized for publication that is planned in a dedicated issue of The Astrophysical Journal Supplement. Apart from the studies mentioned in this paper others have already started and, at the time this paper was written, are in a very advanced stage, including, among the many: time resolved spectroscopy with the specific aim to investigate the change of emitting plasma characteristic with time, a detailed modeling of the effects of X-rays on the environments, with special attention to BN region, the extension of flare statistical study to a more ample range of masses, the study of proplyds. Another item that has been investigated in great detail is the emission from high- and intermediate mass ONC stars (Stelzer et al. 2004) that we have not room to illustrate even briefly.

The results obtained so far illustrate the role that X-rays play in determining the initial evolution of YSOs and their likely role on the early evolution of circumstellar disk and the subsequent planetary system formation. The COUP data are playing and will play a crucial role in our understanding of these quite complex phenomena.

Acknowledgements. COUP is supported by *Chandra* Guest Observer grant SAO GO3-4009A (E. D. Feigelson PI). INAF-Osservatorio

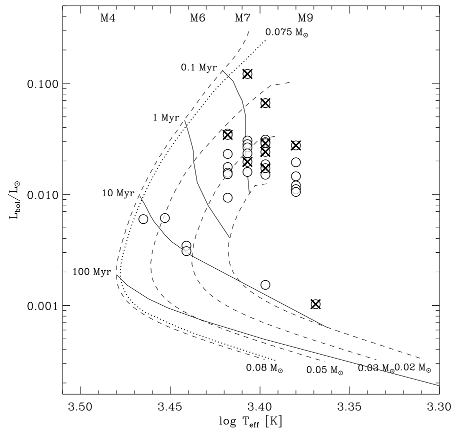

Fig. 12. H-R diagram for the spectroscopically-confirmed ONC BDs (circles) from Slesnick et al. (2004). Objects detected ad X-ray sources in the COUP data are marked by crosses. The evolutionary tracks (dotted lines) and isochrones (solid lines) are from D'Antona & Mazzitelli (1997) (adapted from Preibisch et al. 2004b).

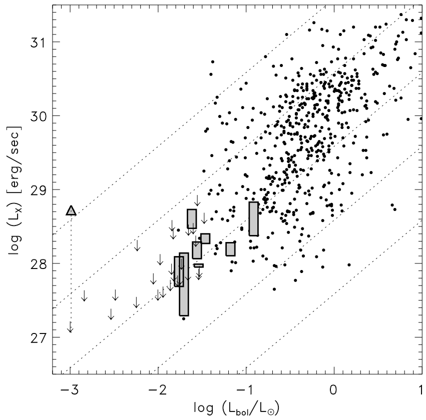

Fig. 13. X-ray luminosity versus bolometric luminosity for the BDs from Slesnick et al. (2004) (gray filled boxes; arrows for upper limits) and low-mass stars from the COUP sample (solid dots). The gray filled boxes for the BDs extend from the characteristic MLB X-ray luminosity (lower edge of the box) to the average X-ray luminosity (upper edge of the box). In one case we show the X-ray luminosity during the flare (gray filled triangle) and the upper limit to the quiescent emission level (arrows). The dotted lines mark L_X/L_{BOL} ratio of 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6} (adapted from Preibisch et al. 2004b).

Astronomico di Palermo scientists acknowledge support by an Italian MIUR PRIN-2002 grant and by an INAF research grant for the years 2002-2004.

References

Bower, G. C., Plambeck, R. L., Bolatto, A. et al., 2003, ApJ 598, 1140

D'Antona, F., & Mazzitelli, I. 1997, MemSAIt 68, 807

Favata, F., Flaccomio, E., Reale, F. et al., 2004, ApJS, submitted

Feigelson, E. D. & Montmerle, T. 1999, ARA&A 37, 363

Feigelson, E. D., Gaffney, J. A., Garmire, G., Hillebrand, L. A., Townsley, L. 2003, ApJ 584, 911

Flaccomio, E., Damiani, F., Micela, G., et al. 2003, ApJ 582, 398

Flaccomio, E., Micela, G. Sciortino, S., et al. 2004, ApJS, submitted

Getman, K. V., Flaccomio, E., Broos, P. S. et al. 2005, ApJS, in press (astroph/04110136)

Grosso, N., Feigelson, E. D., Getman, K. V. et al. 2004, ApJS, submitted

Hillenbrand, L. A. 1997, AJ 113, 1733

Hillenbrand, L. A., Carpenter, J. M. 2000, ApJ 540, 236

Imanishi, K., Koyama, K., Tsuboi, Y. 2001, ApJ 557 747

McCaughrean, M. J. et al., 2005, in preparation

Preibisch, T., Kim, Y.-C., Flaccomio E., et al. 2004, ApJS, submitted

Preibisch, T., McCaughrean, M. J., Grosso, N. et al. 2004, ApJS, submitted

Reale, F. & Micela G. 1998, A&A 334, 1028

Scargle, J. D. 1998, ApJ 504, 405

Slesnick, C. L., Hillenbrand, L. A., & Carpenter, J. M. 2004, ApJ 610, 1045

Stelzer, B., Flaccomio, E., Montmerle, T. et al., 2004, ApJS, submitted

Tsuijmoto, M., Feigelson, E. D., Grosso, N. et al., 2004, ApJS, submitted

Wolk, S., Harnden, F. R., Jr., Flaccomio, E., et al., 2004, ApJS, submitted