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Young stellar populations in the solar neighbourhood

J. López-Santiago[1], G. Micela[1], S. Sciortino[1], and F. Favata[2]

[1] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
e-mail: jlopez@astropa.unipa.it
[2] Astrophysics Missions Division, Research and Science Support Department of ESA/ESTEC, Postbus 299, 2200 AG Noordwijk, Netherlands

Abstract. Stellar X-ray surveys play an important role in understanding the star formation history in our Galaxy in the last billion years (the scale time of coronal activity evolution). In particular, the comparison of observed counts in a given sky direction with predictions by Galactic models can put constraints on the spatial distribution and stellar birthrate of stellar populations. We present the results of our study of the stellar content of the Galaxy in the Solar vicinity using the results of the XMM-Newton Bright Serendipitous Survey (XBSS) Bright Source Sample (BSS) and the ROSAT North Ecliptic Pole survey (NEP). We have used the computational model XCOUNT for predicting the number of coronal sources and their spectral type distribution in the surveyed area. The comparison of the predictions with the observations supports a scenario with an increasing stellar formation rate during the last billion years. Nevertheless, we observe an excess of dwarf FGK stars in the observations, which can be due to both the existence of a young stellar population or to a number of M stars in binary systems with a yellow primary.

Key words. galaxy: stellar content – stars: activity – stars: coronae – stars: formation – stars: magnetic fields – X-rays: stars

1. Introduction

Stellar X-ray surveys are one of the most powerful tools for investigating the stellar populations of the Galaxy. The comparison between the number of observed stars and predictions derived from X-ray galactic models yields constraints to the properties of stellar populations, such as their spatial distributions and the stellar birthrate.

Current optical galactic models (eg. Bahcall & Soneira 1980; Robin & Crézé 1986) can successfully predict the total number of stars and some photometric and spectroscopic properties such as spectral types, but they give little information about the nature and characteristics of the observed stellar population. For instance, they do not distinguish between old and zero age low mass main sequence stars since luminosity changes in the optical band are negligible on the main sequence. On the contrary, X-ray luminosity changes up to 3–4 orders of magnitude during the main sequence life of low mass stars. It is well known from the study of young open clusters

Send offprint requests to: J. López-Santiago

that magnetic activity traced by coronal X-ray emission evolves during the stellar life. The average L_x decreases from $\sim 10^{30}$ erg s^{-1} to $\sim 10^{27}$ erg s^{-1} during the life of normal late-type stars (Micela et al. 1985, 1988; Guedel et al. 1997; Feigelson & Montmerle 1999). This decrease mostly occurs between the Zero Age Main Sequence and the solar age, while it is nearly negligible during the pre-main sequence phase. Thus, X-ray surveys are very useful for studying the stellar population in the (near) Galaxy in a range of age that cannot be explored with different techniques.

2. Shallow surveys for studying the young stellar population in the solar neighbourhood

As a consequence of the decrease of X-ray luminosity with age, X-ray flux-limited surveys detect young stars up to larger distances than old ones. Since young sources have smaller scale heights than the limiting distance of the survey (see Micela 2003, and references therein) shallow stellar X-ray selected samples will be dominated by young stars while old stars will be the dominant population in deep high-latitude stellar X-ray samples. This effect makes shallow surveys excellent laboratories for the study of the young stellar population of the near Galaxy.

2.1. Previous results

One of the first results based on the analysis of the Extended Medium Sensitivity Survey of *Einstein* (EMSS, Gioia et al. 1990) was the detection of an excess of yellow stars in the observations (Favata et al. 1988) later confirmed to be due to young stars (Favata et al. 1993; Sciortino et al. 1995). An excess of young stars in the solar neighbourhood was also detected by Exosat and Rosat (eg. Tagliaferri et al. 1994). These results exclude scenarios with decreasing stellar birthrate in the last billion years, although they are unable to discriminate between a constant and an increasing stellar birthrate hypotheses, because of the limited sample size (Micela et al. 1993). The analysis of the Chandra Deep Field-North (CDF-N, Brandt et al. 2001) shows a lack of F, G and K dwarfs with respect to the predictions, while the number of dM stars agrees very well with that predicted by the model (Micela 2003; Feigelson et al. 2004). The observed lack of yellow stars is in the opposite direction of the discrepancy found in the EMSS, although it must be noticed that the CDF-N is dominated by old-disk stars while young stars are dominant in the EMSS.

The discrepancy between the results of shallow and medium-deep surveys could be explained by a non-constant stellar birthrate and/or incorrect assumptions on the spatial distribution of stars and its dependency on age in the galactic model. An increased star formation rate in the last billion years would account for the excess of young stars in shallow surveys, while a density distribution decreasing with distance from the Galactic plane much more steeply than the assumed exponential shape (e.g. Guillout et al. 1996; Haywood et al. 1997) would account for the lack of old sources in medium and deep surveys. In this context, Chandra and XMM-Newton surveys could be able to discriminate between these two possible scenarios, thanks to their high sensitivity (Micela 2003).

2.2. The BSS and the NEP contribution

Recently, two new shallow surveys have been studied by our group (see, López-Santiago et al. 2006; Micela et al. 2006): the Bright Source Sample (BSS) of the XMM-Newton Bright Serendipitous Survey (XBSS, Della Ceca et al. 2004) and the stellar sample of the ROSAT North Ecliptic Pole (NEP, Henry et al. 2001) survey. Both have similar properties (see Table 1) and can be used together for studying the stellar populations in the vicinity of the sun.

The XMM-Newton Bright Serendipitous Survey (XBSS) was conceived with the aim of complementing the results obtained by medium and deep X-ray surveys. It contains two flux limited samples of serendipitous XMM-Newton sources at galactic latitudes $|b| > 20°$: the XMM Bright Source Sample (BSS) containing the sources detected in the energy range 0.5 – 4.5 keV with count-

Table 1. Properties of the BSS and the NEP surveys

Sky covered (deg^2)	Energy range (keV)	Count-rate ($cnt\ s^{-1}$)	Flux limit ($erg\ cm^{-2}\ s^{-1}$)	# of stars	Max. distance† (pc)
Bright Source Sample (BSS)					
28.1	0.5 – 4.5	1×10^{-2}	6.8×10^{-14}	58	110
North Ecliptic Pole (NEP)					
81.0	0.1 – 2.4	$2\times10^{-3} - 1.6\times10^{-2}$	$1.6\times10^{-14} - 1.3\times10^{-13}$	151	228 – 80

† Using a typical X-ray luminosity $L_X = 10^{29}$ erg s^{-1}.

rate $\geq 10^{-2}$ cnt s^{-1} in EPIC-MOS2, and the XMM Hard Bright Source Sample (HBSS) with sources revealed in the energy range 4.5 – 7.5 keV with count-rate $\geq 2 \times 10^{-3}$ cnt s^{-1} (see Della Ceca et al. 2004,for details). For a Raymond-Smith spectrum with temperature 0.7 keV, typical of an active coronal source, the count-rate limit in the two chosen bands corresponds to an unabsorbed flux limit of 6.8×10^{-14} erg cm^{-2} s^{-1} and 3.7×10^{-13} erg cm^{-2} s^{-1}, respectively. With this sensitivity, the XBSS complements deeper XMM-Newton and Chandra surveys with fluxes ranging from 10^{-14} to 10^{-15} erg cm^{-2} s^{-1}. From the point of view of the stellar content, only the BSS is useful, since it contains all the 58 stellar sources observed while only 2 are revealed in the HBSS. Thus, only the BSS can be used for studying the stellar population.

The ROSAT North Ecliptic Pole covers a $9° \times 9°$ area centred on the Galactic North Ecliptic Pole (l = 96.4°, b = 29.8°). This is the sky region with the highest sensitivity observed during the ROSAT All Sky Survey (RASS), with a total exposure time of ∼ 40 ksec at the pole. The galactic latitude together with the moderate sensitivity permits to observe young stars close to their scale height.

Combining the results of both samples one can take advantage of their specific characteristics. The large effective area of the XMM-Newton satellite permits to study the X-ray spectral properties of all the observed sources. The other particularity of the BSS is that it is unbiased at the flux limit; i.e., no *a priori* assumption has been made when selecting the sample. Hence, the obtained results are valid for the entire Solar Neighbourhood. On the other hand, the large sky area covered by the NEP survey provides a large sample of stars which allows some statistical analysis.

3. Observational results of the Bright Source Sample

As mentioned in Sect. 2.2, the BSS is unique since it is the only survey of this kind where X-ray spectroscopy can be obtained for all the stars detected. The results of fitting multi-temperature models to the EPIC spectra of the stars in the sample (see Fig. 1) show that their emission is typical of intermediate-age stars (López-Santiago et al. 2006). Best results are found when using a 2-temperature model with temperatures around 0.31 keV and 0.98 keV with essentially the same contribution ($EM_1/EM_2 \sim 1$). The low spread found in the temperature distributions of both thermal components, with Gaussian $FWHM$ of 0.15 and 0.19 keV, respectively is remarkable. Similar thermal properties were found by Briggs & Pye (2003) for the coronae of low rotating solar-like Pleiads. This is consistent with the BSS being dominated by young main sequence stars. Due to the low signal-to-noise ratio of some sources, a 2T-model could not be fitted for all the stars. But the broad spread in temperatures found for these sources

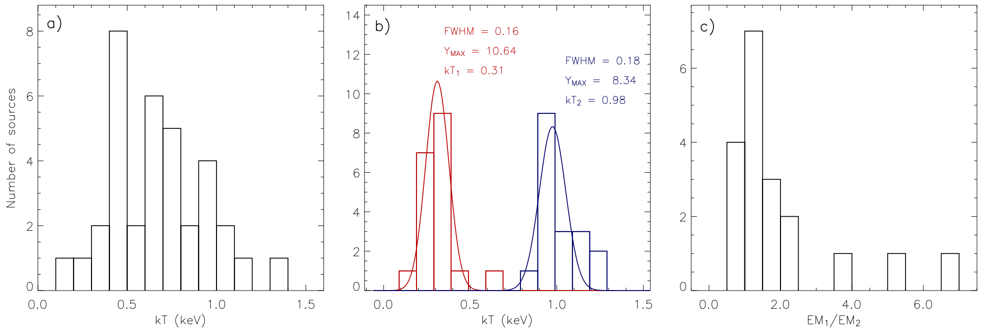

Fig. 1. a) Temperature distribution for the sources where a 1T-model has been fitted. **b)** Distribution of T_1 and T_2 of the stars where two thermal components have been fitted. **c)** Distribution of EM_1/EM_2 of the stars in figure b).

(see Fig. 1a) suggests the presence of two unresolved thermal components in their X-ray spectra, as in the case of the stars with higher signal-to-noise ratios.

From the cross-correlation of the stars in the BSS with the 2MASS database, we find that all their infrared counterparts are on the main sequence in the JHK color-color diagram (see Fig. 2 left). No peculiar objects or stars with infrared excess seem to be present. Only using the SIMBAD database it has been possible to identify two peculiar (WD + M star system) objects and a young pre-main sequence star (see, López-Santiago et al. 2006). Table 2 shows the results of the spectral classification of the stars of the sample using both IR colors and optical spectra.

Table 2. Summary of the spectral classification of the stellar X-ray sources in the BSS and the NEP. Stars with spectral types F6 − F9 are grouped with G stars due to their similar X-ray properties.

	# of sources	
Sp. Type	BSS	NEP
(Be, CV, WD)	3	7
A	2	3
F-F5	6	10
F6-G	12	37
K	21	53
M	14	41
Total	58	151

4. Observational results of the North Ecliptic Pole

Contrary to the BSS survey, no X-ray spectral fitting information of the NEP sources is available. Nevertheless, the number of stars detected in the NEP survey is ∼ 3 times higher than in the BSS, since the area covered by the NEP is ∼ 3 times larger than that covered by the BSS. Thus, the NEP survey allows to obtain statistical results when dividing the sample in spectral sub-types.

The optical follow-up of the stars of the sample (Micela et al. 2006) has shown that the NEP is mainly dominated by K-M stars, contributing the 65% of the total (see Table 2). Also G stars have an important contribution (∼ 25%) but not the A and F stars which only contributes the 10%. As in the case of the BSS, the near-IR counterparts of the NEP X-ray sources are on the main sequence (see Fig. 2 right).

5. Model predictions

The X-ray Galactic model XCOUNT (Favata et al. 1992; Micela et al. 1993) has been used for predicting the number and properties of the coronal sources expected in both the BSS and the NEP survey. The model is

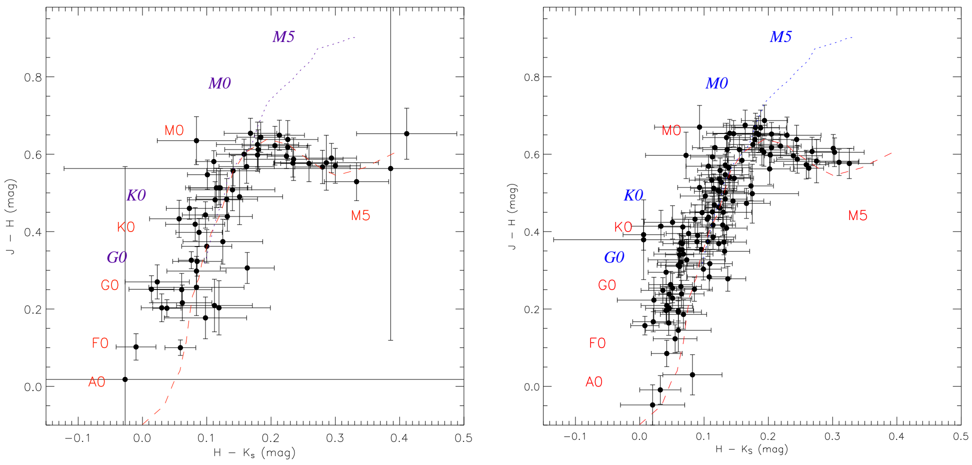

Fig. 2. Left: Color-color NIR diagram for the stars in the BSS (López-Santiago et al. 2006). Dashed and dotted lines are the main sequence track and the giant branch defined by Bessell & Brett (1988) transformed here to the 2MASS system (see text). Spectral types of the main sequence are labeled with roman font, at the corresponding $J - H$ value but offset in $H - K_s$. Italic font has been utilized for labeling the spectral types of the giant branch. **Right:** Same as right figure, for the NEP sample (Micela et al. 2006). Here, only those IR counterparts with quality flag 'AAA' in 2MASS has been plotted.

based on the stellar spatial densities of the Bahcall & Soneira model (Bahcall & Soneira 1980; Bahcall 1986). Although the Bahcall & Soneira model includes both an exponential disk and a spheroid, XCOUNT considers only the disk component due to the low X-ray luminosity of spheroid stars (see Favata et al. 1992). Different scale heights have been adopted for separating the population in three different age ranges: 100, 200 and 400 pc for 0.01–0.1, 0.1–1, and > 1 Gyr respectively. In the same way, X-ray luminosity functions (XLFs) have been utilized for the distinct age ranges: the youngest stars with ages 0.01–0.1 Gyr are assigned the ROSAT XLF of the Pleiades members (Micela et al. 1996); intermediate-age stars with ages 0.1–1 Gyr are assigned the ROSAT XLF of the Hyades (Stern et al. 1995); and the older ones ($t > 1$ Gyr) are assigned the XLF of *Einstein* studies of nearby old-disk stars (Schmitt et al. 1985; Maggio et al. 1987; Barbera et al. 1993).

5.1. Comparison with the observations

For both BSS and NEP, XCOUNT predicts the X-ray population to be dominated by intermediate-age and old stars with almost the same contribution. Indeed, the relative contribution of young, intermediate-age and old disk stars changes when using different stellar birthrates, but intermediate-age stars continue to be dominant (see Micela et al. 1993; López-Santiago et al. 2006,for a further discussion). The total number of predicted stars also changes when using different star formation rates. For instance, the best results for the BSS are obtained in a scenario with increasing star formation rate (López-Santiago et al. 2006). Nevertheless, the predicted spectral distribution of the stars does not match that observed in the surveys (see Fig. 3). As in the case of the Extended Medium Sensitivity Survey of *Einstein* (EMSS, Gioia et al. 1990), an excess of FGK stars is observed.

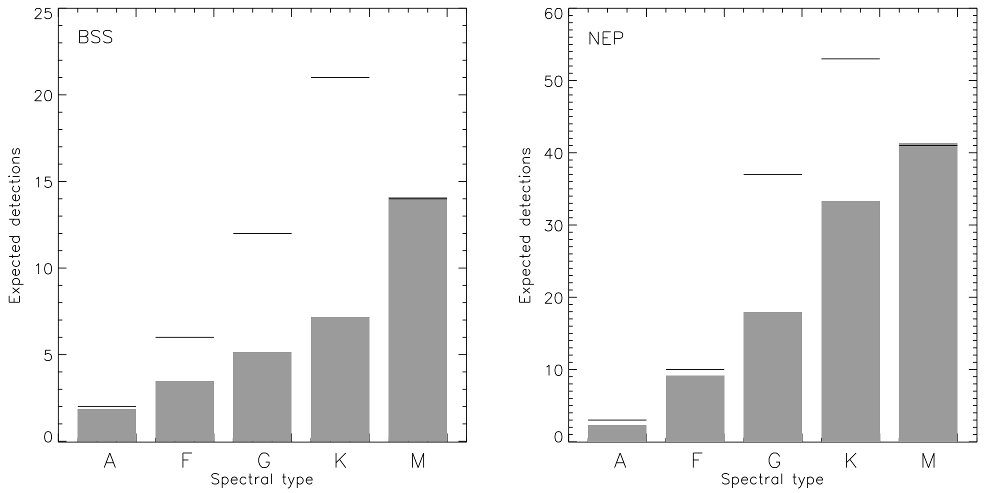

Fig. 3. Spectral type distribution of the stellar population of the BSS (left) and NEP sample (right). Bars represent predictions by XCOUNT model using constant birthrate. Horizontal segments are the observed stars.

5.2. The nature of the observed excess

Favata et al. (1993) and Sciortino et al. (1995) confirm the excess of yellow stars in the EMSS is due to young stars. By analogy, the same situation might be expected for the BSS and the NEP. However, the study of the X-ray spectrum of the sources in the BSS and the position in the near-IR color-color diagram of the 2MASS counterparts of the stars in the BSS and the NEP (see Sects. 3 and 4) show that both samples are dominated by intermediate-age and old main sequence stars. A quick inspection of the observed $\log N$-$\log S$ curve in both the BSS and the NEP (Fig. 4) shows that the observed distribution of sources in those samples runs parallel to the predicted one at weak fluxes, with an excess in the observations. At higher rates, the observed distribution shows a bending. This is indicative of a population with a small scale height and high X-ray fluxes. High activity and small scale height are typical of young populations (Micela et al. 2006). However, the bending expected for a $10^7 - 10^8$ years-old population should appears at a flux of $\sim 10^{-3}$ cnt s^{-1} (to be compared with the observed one of $\sim 10^{-2}$ cnt s^{-1}). The population responsible for such a bending should have either an intrinsic X-ray luminosity one order of magnitude higher than the youngest population accounted for in the model ($10^7 - 10^8$ years), or a scale height ~ 3 times smaller than it (Micela et al. 2006) and must be concentrated only on FGK stars. Moreover, its density should be ~ 2 times higher than that of the youngest stars. This discounts the RS CVn systems as responsible for the excess since their density is very much lower.

From the point of view of the star formation, it is difficult to explain the presence of a stellar population with the characteristics described above. Besides, such a bright X-ray population should have been detected in the nearby flux limited surveys of stellar X-ray emission (Maggio et al. 1987; Schmitt & Liefke 2004). To better understand the nature of this observed excess, Micela et al. (2006) divide the NEP sample into spectral type subsamples, taking advantage of the relatively large number of stars in this survey. Bearing in mind the results of the comparison between the model predictions and the observations (Fig. 3 right) they divide the sample into three subgroups: A-F stars, G-K stars, and M stars (see Fig. 4 right). In general, the earliest types contribute little to the global $\log N$-

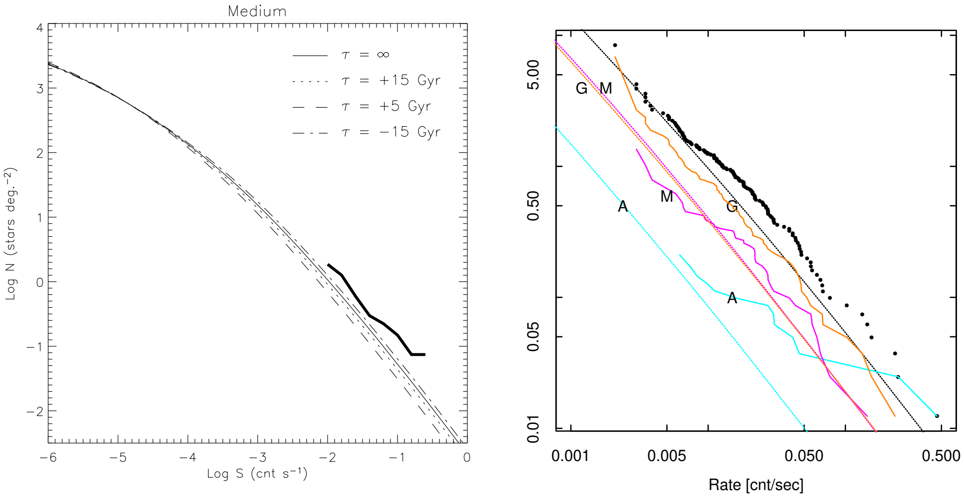

Fig. 4. Left: Log N–Log S predicted assuming an exponential ($Ae^{-t/\tau}$) stellar birthrate with $\tau = \infty$, +15, +5 and -15 Gyr, compared with the BSS results (thick solid line) for the fields observed with the medium filter (energy band 0.5–4.5 keV). Flux is expressed in EPIC/XMM-Newton count-rate. **Right:** Observed and predicted Log N–Log S toward the NEP. Flux is expressed in Rosat/PSPC count rate. The upper line is the total expected curve and the points are the observations. The lower line represents the predictions for A and early F stars, while the two dotted over-imposed lines are the predictions for G-K and dM stars, respectively. The observed A and early F stars are marked by the lower irregular line, while observed dM stars are the intermediate irregular line, and the upper one is the observed Log N–Log S of dG and dK stars.

log S and the excess at high fluxes can be attributed to some peculiar dA stars (Micela et al. 2006). On the contrary, dG and dK stars are clearly above the predictions at every flux. At the same time, the dM stars are quite in agreement with the predictions. Thus, the bending of the observed total log N-log S seems to be an artifact due to a combination of a simultaneous small deficiency of dM stars and a minor excess of yellow stars at low count-rates (Micela et al. 2006).

A different explanation for the observed excess can be given in terms of binary stars. Taking into account that both surveys are dominated by intermediate-age and old main sequence stars, the excess of FGK stars in the observations can be explained by the presence of a population of binary systems made up of a yellow primary and a secondary dwarf M. In that case, the optical and the near-IR colors would be dominated by the primary while the X-ray emission would be due to both companions. In this sense, the excess of yellow stars in the observations could be an artifact produced by the binaries in the sample. This hypothesis does not account for the total number of stars, but only for the differences in the spectral distribution between observations and predictions. To correct such a difference, a density distribution decreasing with distance from the Galactic plane much more steeply than the assumed exponential shape or an increasing stellar birthrate in the last billion years are needed.

6. Conclusions

The results of comparing the stellar content of the BSS and the NEP surveys with Galactic model predictions show that a scenario with a constant or a slowly increasing stellar birthrate in the last billion years is more suitable for both surveys. From the study of the X-ray spectra of the BSS and the position in the near-IR color-color diagram of the 2MASS counterparts of the X-ray sources in the BSS and the NEP (López-Santiago et al. 2006; Micela et al. 2006), we infer that both samples are dominate by intermediate-age and old stars. The discrepancy between the spectral distribution of observations and predictions could be due to a young stellar population, as in the case of the EMSS, and/or to a number of active binary systems made up of a yellow dwarf and an M star.

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