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The Stellar Coronal Component of the Galaxy: II - An Analysis of the Stellar Content of the *Einstein* Extended Medium Sensitivity Survey

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Abstract. We present a detailed analysis of the stellar content of the *Einstein* Extended Medium Sensitivity Survey (EMSS). The analysis consists of a comparison between the observed source counts and expectations computed on the basis of the known X-ray luminosity functions for disk population stars and established models for the structure of the Galaxy. We show that the presence of an excess of X-ray luminous "yellow" stars, already found with the analysis of the stellar content of the *Einstein* Medium Sensitivity Survey (MSS), is confirmed by the EMSS, whose substantially larger size sample allows to draw conclusions with a higher statistical significance than the MSS, and discuss the nature of this stellar population. Additionally, we show that to ensure the coherence between the observed number of dwarf M stars in the EMSS with the X-ray luminosity functions derived from optically selected sample, it is necessary to take into account the effects deriving from the variation of X-ray luminosity with stellar age, as well as the effect of stellar multiplicity.

Key words: stellar contents of the Galaxy – X-ray stellar counts

1. Introduction

The X-ray emission properties of normal stars of spectral type later than A have been the object of extensive studies based on the imaging detectors on board the *Einstein* and *EXOSAT* observatories. The surveys conducted up to date fall roughly into two major classes: the optically selected and the X-ray selected. The majority of the published surveys fall in the first category, in which the survey sources are selected from optical catalogues (usually volume or magnitude limited). A summary of these studies can be found, among others, in many recent reviews (Rosner, Golub & Vaiana, 1985, Vaiana & Sciortino, 1987, Vaiana et al. 1992, Sciortino 1993).

X-ray selected surveys are on the other hand based on the complete identification of X-ray sources detected in a flux-limited survey. For stellar surveys, up to the time of our writing (April 1994) the best studied X-ray selected stellar sample is that extracted by the *Einstein* Extended Medium Sensitivity Survey (EMSS, Gioia et al., 1990) in which Stocke and collaborators (Stocke et al., 1991) have identified about 215 X-ray sources with normal stars.

Favata et al. (1988) have previously investigated the consistency between stellar X-ray luminosity functions based on optically-selected, volume-limited stellar surveys and the result of X-ray selected surveys. As result of this work they presented the evidence for an excess of X-ray luminous "yellow" stars in the X-ray selected samples, that they tentatively identified with a population of active RS CVn-like binaries, or a population of active young late-type stars. The limited small size of the available samples at that time did allow to draw conclusions only at 99% confidence level.

The rationale for conducting the analysis presented here is to determine the consistency between the information on X-ray luminosity of normal stars determined locally or within age-homogeneous nearby open clusters with the global information on X-ray emission available from (flux-limited) sky surveys such as the Extended Medium Sensitivity Survey (based on larger volumes and usually larger samples of less well studied objects). To this purpose we have computed, with the help of a numerical computer code (the so-called X-Count X-ray Galactic model, Favata et al., 1992, hereafter Paper I), the expected number of X-ray coronal sources for each spectral type in the EMSS fields and their distributions in apparent magnitude, color and f_X/f_V ratio (under the conditions described in detail later on), and have compared the

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predictions with the observed source counts and distributions.

The rationale for re-doing the analysis that was performed by Favata et al. (1988) is twofold: first, the EMSS stellar sample is almost three times larger than the best previously available samples, and the quality of optical data is much better than that available to Favata and collaborators at the time of their writing, and therefore its analysis allows us to draw statistically sounder conclusions. Second, we have used a more sophisticated numerical model than the one used in Favata et al. (1988), which takes into account effects not previously considered, such as the influence of stellar age on the level of X-ray emission, the effects of unresolved binaries, and the variation of interstellar X-ray absorption with source spectrum, and which is capable of predicting not only integral source counts but also magnitude, color and X-ray flux distributions (Paper I). Moreover we have now a more detailed knowledge of the X-ray luminosity functions than that available to Favata et al. (1988) to the time of their writing.

2. Assumptions made in the computations

2.1. Limiting sensitivity

Any correct prediction of source counts requires a detailed knowledge of the limiting sensitivity of observations. In the case of a Wolter type I imaging X-ray telescope with an imaging proportional counter as detector (such the *Einstein* IPC or the ROSAT PSPC) the sensitivity changes across the field of view because of mirror vignetting and detector non-uniformities. For this reason we need a detailed knowledge of the instrumental characteristics to properly evaluate the sensitivity of the observations. Note that the limiting sensitivity distributions published for the EMSS (which only give the global sensitivity distribution, with no positional information) are not sufficient for the purposes of the present work, as we need to use the limiting sensitivity as a function of sky position and its variations at different positions in the IPC field of view.

To evaluate the limiting sensitivity of EMSS observations we have followed the procedure described by Harris et al. (1993), to which the reader is referred for more details.

Here we notice that the actual limiting sensitivity (in count/sec) can be obtained with a resolution of 2.4' x 2.4' resulting in about 360 independent resolution element on which to perform computation for each IPC field. This would result in an unjustified (given other intrinsic uncertainties) computation time while we have found that the adoption of 5 distinct spatial regions (cf. Table 1) each with its limiting sensitivity would introduces an uncertainty in the predicted counts of 1%, well below the uncertainties due to all other model assumption.

Table 1. IPC constant sensitivity region

Region	Solid Angle sq. degree	Mean Relative[a] Sensitivity
1	0.0280	1.00
2	0.1392	0.92
3	0.1536	0.81
4	0.2240	0.55
5	0.0400	0.33
Total	0.5776	

a - This number indicate the sensitivity of given region with respect the sensitivity on-axis, i.e. if the on-axis sensitivity is 2 $\times$ 10^{-13} ergs sec^{-1} cm^{-2}, the sensitivity of region 5 is 6.04 $\times$ 10^{-13} ergs sec^{-1} cm^{-2}. We indicate mean values since actual values depend on properties characterizing the given exposure.

Therefore, for each of the EMSS fields we have computed 5 representative values of sensitivity, together with their relative solid angle and sky position, which have been then used for all the computations presented here.

2.2. Coronal Emission Models

We have assumed that the incident X-ray spectrum from a stellar source can be modeled by a Raymond-Smith thermal spectrum (Raymond & Smith, 1977, Raymond, 1988) from a solar abundance plasma, characterized by a single free parameter, the temperature. Following Kashyap et al. (1992) we have also considered a two temperature model with $T_{\rm low} = 2.5\ 10^6$ K and $T_{\rm high} = 1.6\ 10^7$ K whose free parameter is the ratio of the emission measure of the two thermal components. Based on the IPC spectral stellar survey (Schmitt et al. 1990) we have considered values of this ratio in the range 0.1 to 10.

2.3. Distribution of interstellar H

The absorption of X-rays in interstellar space is mostly due to the mix of "metals" present in the interstellar gas. However, as no reliable tracer is known for the heavier elements, it is commonly assumed that the interstellar gas has an uniform composition and therefore that the density of X-ray absorbing material is well correlated with the density of interstellar hydrogen.

For the present work we have used a published model for the distribution of neutral hydrogen in the Galaxy (Lockman, 1984), which is based on radio observations at 21 cm, and which has been shown to be in good agreement with the interstellar UV absorption of stars of known distance. This provides additional support for the assumption of good correlation between X-ray absorption and neutral hydrogen column density. Note however that such model does not take into account the presence of individual interstellar clouds, and therefore the predicted H column density in each direction in the sky is a typical value.

We have verified that, given the nature of the computations presented here involving $\sim 10^3$ directions, the usage of a more detailed interstellar absorption model, obtained by normalizing the total H column density in each given direction to the value of total column density detected in radio surveys (Heiles & Cleary, 1979, Cleary, Heiles & Haslam, 1979, Stark et al., 1987) does not substantially modify our results.

2.4. X-ray luminosity functions

We have used maximum likelihood X-ray luminosity functions obtained from *Einstein* IPC data in the (0.16-4.0) keV energy range. The adoption of luminosity functions allows to take naturally into account the possible dependence of coronal emission level from "hidden" parameters, as well as the occurence of long and short-term variability of coronal emission, such as that observed in the Sun.

The X-ray luminosity functions used in the computations presented here are based either on volume limited survey of stars in the solar neighborhood or on surveys of stellar X-ray emission from the nearby Pleiades and Hyades open clusters (which supply an intrinsically age-homogeneous sample). Their usage is therefore subject to the assumption that the stars in the solar neighborhood and in the Pleiades and Hyades are, from the point of X-ray emission, representative of the global Galactic population.

For the analysis presented here we have considered main sequence disk population stars as the main contributors to the stellar X-ray counts, and have furthermore considered, as explained later, the contribution of both normal giant stars and active binaries (of the RS-CVn type) to the X-ray source counts. We have used X-ray luminosity function obtained from stars in the solar neighborhood for the following ranges of main sequence stellar masses.

1) A stars ($0.0 \leq B-V < 0.3$): Based on the sample (4 detections and 12 upper limits) within 30 pc observed with the IPC (Schmitt et al., 1985).

2) F stars ($0.3 \leq B-V < 0.5$): Based on the sample (31 detections and 11 upper limits) within 30 pc observed with the IPC (Schmitt et al., 1985).

3) For dwarf old disk population stars of spectral types G, K and M we have adopted the X-ray luminosity functions obtained from the surveys of stars within 25 pc observed with the IPC: the G dwarf sample ($0.5 \leq B-V < 0.8$) consists of 32 detections and 29 upper limits (Maggio et al., 1987), the K dwarf sample ($0.8 < B-V \leq 1.45$) of 19 detections and 14 upper limits (Barbera et al., 1993), the early M dwarf sample ($1.45 < B-V \leq 1.70$) of 18 detections and 27 upper limits (Barbera et al., 1993), the late M dwarf sample ($B-V > 1.70$) of 5 detections and 4 upper limits (Barbera et al., 1993).

4) For dwarf intermediate disk population stars of spectral types G, K and M we have adopted the X-ray luminosity functions obtained from the survey of the Hyades (Micela et al., 1988). The G star sample consists of 11 detections and 2 upper limits, the K star sample of 16 detections and 14 upper limits, the early M star sample of 14 detections and 32 upper limits.

5) For dwarf young disk population stars of spectral types G, K and M we have adopted the X-ray luminosity functions obtained from the survey of the Pleiades (Micela et al., 1990). The G star sample consists of 21 detections and 31 upper limits, the K star sample of 41 detections and 85 upper limits, the early M star sample of 4 detections and 35 upper limits. Both the Einstein surveys of the Hyades and of the Pleiades do not allow to evaluate the luminosity functions of the late M stars. The recent ROSAT observations of the Hyades (Stern et al. 1992,1994) and of the Pleiades (Stauffer et al. 1994; Micela et al. 1993a,1994) have not substantially changed the situation in this respect.

In the case of the disk giants we have used X-ray luminosity functions obtained from stars in the solar neighborhood for the following mass ranges.

1) F and G stars ($0.6 \leq M_{\rm V} \leq 0.8$), based on the sample (22 detections and 16 upper limits) within 100 pc observed with the IPC (Maggio et al. 1990)

2) K and M stars ($-0.8 < M_{\rm V} < 0.6$), based on the sample (7 detections and 34 upper limits) within 100 pc observed with the IPC (Maggio et al. 1990)

In the case of the RS CVn's we have adopted the X-ray luminosity function we have computed from the sample of RS CVn detected with the *Einstein* Observatory (Majer et al. 1986) within 30 pc from the Sun to reduce the bias we would introduce by including in the calculation of the X-ray luminosity function the more distant and likely more exceptional known RS CVn's.

2.5. Age of source population

The variation of X-ray luminosity with stellar age cannot, for the purposes of the present work, be neglected, because age seems to be a major parameter in determining the X-ray luminosity of a stellar coronal source (see Vaiana et al., 1992 and references therein). Variations in X-ray luminosity due to age differences are in fact observed to be stronger than the variations in X-ray luminosity due to differences in the "classical" parameters such as stellar mass or effective temperature. In the context of our model the variation of stellar X-ray emission levels with stellar age is made more relevant by the strong difference in spatial distribution between young and old stellar sources of the same spectral type, which in turn influences the predicted number of sources (Micela, Sciortino & Favata 1993b, hereafter Paper II).

We have therefore used, for the calculations presented here, a modified implementation of the Bahcall and Soneira Galaxy model (Bahcall & Soneira, 1980, Bahcall, 1986), which includes sub-populations of different ages, as described in Papers I and II, to which the reader is referred for details. In Paper II we have shown (i) that the implemented modifications do not change significantly the expected number of optical counts (cf. Figure 3 of Paper II), and (ii) that using a model which takes into account the age distribution of the source population has a large effect on predicted source counts, compared with the uncertainties of the computation. Therefore in the following we will always use source counts computed assuming a constant stellar birthrate, which has been shown in Paper II to be compatible with the EMSS source counts.

2.6. The unresolved binaries

The stellar density function used in Galaxy models such as the Bahcall and Soneira Galaxy model is intended to be (a best approximation to) the true number density function of stars, regardless of whether they are single stars or belong to multiple systems. When comparing the results from such a model with observations it is therefore necessary to consider the presence of unresolved binaries in the observed sample.

The effect due to the presence of unresolved binaries is not very large in the case of optical star counts, as at most the brightening due to binarity can be a factor of two (if the two components of the system are of equal luminosity). This corresponds to a brightening of 0.75 magnitudes, while the color change is limited to differences in color indexes smaller than 0.05. Additionally, as discussed by Reid (1991) the effect due to the uncertainties in the color-magnitude relations, combined with the increased luminosity (and the correspondingly increased space volume surveyed) tend to compensate for the 'missing' stars hidden in unresolved binaries.

Table 2. Assumed parameters in model computation

Age (years)	Scale Height (pc)	Prototype X-ray Lum. Fun.	Coronal Temperature (keV)
$10^7 - 10^8$	100	Pleiades	1.1
$10^8 - 10^9$	200	Hyades/Young Disk	0.5
$10^9 - 10^{10}$	400	Old Disk	0.3

In the X-ray domain the picture is different, as the effect of binarity is more dramatic. The combination of an inactive G dwarf with an active M dwarf can for example easily increase the apparent X-ray luminosity of the G dwarf by one order of magnitude or more, while leaving its optical photometric properties almost unchanged. Therefore the existence of unresolved binaries must, in the X-ray case, be treated in detail before a comparison with observed source counts and distributions can be made.

Note that as far as the X-ray luminosity functions are concerned, since they are based on well studied samples of nearby stars, it can be assumed that the effect due to the binary systems has already been taken into account. On the other hand, for X-ray based surveys such as the EMSS, close binaries are likely to be unresolved and therefore have to be dealt with by separately considering the X-ray luminosity of both components.

One additional problem in the present context is that we have to consider separately the contributions of stars of different age groups. The so-called present-day luminosity function includes all the stars existing today, while what we need are luminosity functions separated by age groups. We have approached this problem by starting with the present-day optical luminosity function of Rana (1990) based on some of recent re-determinations at low-mass end and have derived, as discussed in detail in appendix A, the optical luminosity function of *single* stars.

To quantify the effect of the unresolved binaries we show in Figure 1a the predicted B-V distributions for EMSS star counts adopting the X-ray luminosity functions derived for the *single* stars under the assumption of stellar populations of three distinct age ranges with characteristics summarized in Table 2. We have then repeated the same calculations but adopting X-ray luminosity functions that accounts for the presence of unresolved binaries (cf. Figure 1b). In this last case the number of predicted stars in the EMSS is significantly larger than in the first case, and Figure 1 clearly shows that this effect is more pronounced for low-mass stars.

3. The X-ray sample used in this work

To the date of this writing (April 1994) the EMSS (Gioia et al., 1990) is the largest essentially completely identified sample of sources discovered in a X-ray flux limited imaging survey. The subsample composed by the stellar coronal sources detected in the EMSS is the reference sample adopted in all the following analyses.

The EMSS consists of all the 835 serendipitous sources detected at 4 σ level (or higher) in 1435 *Einstein* IPC images away from the galactic plane region ($|b| > 20°$). The final result of the identification process of essentially the entire EMSS source sample has been reported (Stocke et al., 1991). As a result of this work 813 sources have been uniquely identified. For 32 out of the 835 sources the identification is more complex; 12 of these are stars likely to be members of binary systems (cf. Table 5b of Stocke et al., 1991), and in these cases we have adopted

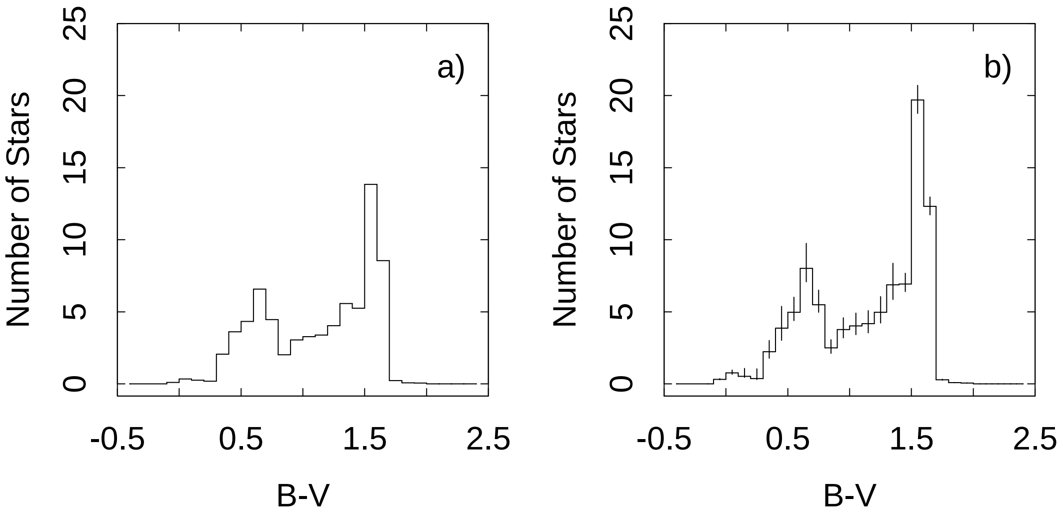

Fig. 1. The effect of the presence of unresolved binary systems on the computed color distribution. On panel a) we show the color distribution generated by the X-Count code without accounting for the presence of unresolved binaries, on panel b) the same distribution including the effect of unresolved systems. The calculations have been performed according to the model parameters listed in Table 2. The error bars shown on panel b) are due to the uncertainty on X-ray luminosity functions, evaluated using the 16% and 84% quantile luminosity functions.

the combined B-V color and magnitude for the systems. For 5 sources two possible stellar counterparts physically unrelated have been proposed, and in these cases we have adopted the preferred identification listed in Table 5a of Stocke et al., (1991). Finally, 2 sources could have both a stellar and a non-stellar counterparts (cf. Table 5c of Stocke et al., 1991), and in these cases we have retained the stellar counterparts in our reference sample. Hence the sample of stellar coronal source can be considered as completely identified. The identifications reported by Stocke et al. (1991) do not suffice for the analysis we want to perform, because the spectral types given are only approximate and because they often lack information such as color, distance, binarity, luminosity class, etc. that are essential in this context. Because of that we have limited our analysis to the subsample of 953 EMSS fields (kindly provided us by T. Fleming) whose stellar content have been studied in great detail by Fleming (1988). In his study Fleming (1988) has considered 131 stellar sources[1] out of the 164 finally listed, for the same subsamples of EMSS fields, by Stocke et al. (1991), obtaining accurate spectral types and luminosity classes through intermediate resolution spectroscopy and determinig stellar rotation rates and eventual binary nature through limited echelle spectroscopy. Having studied a large fraction of the EMSS stellar sources, Fleming discovered that a fraction of them are not 'normal' stellar main-sequence coronal sources. Out of the 131 sources studied, 16 have been identified as RS CVn-type binaries, 5 as W UMa-type binaries, 4 as Pre-Main Sequence (PMS) stars, 1 as a FK Coma type, and 1 as a BY Dra type. Out of the 31 stellar identification added by Stocke et al. (1991), 6 turn out to be Pre-Main Sequence stars and 1 a W UMa-type binary.

We have taken the $B-V$ value from Fleming (1988) for the stars in his sample, while for the remaining stars added by Stocke et al. (1991), we have evaluated $B-V$ (taken from Allen, 1973) from spectral type assuming those stars belong to the main sequence. We recognize that because of the reduced amount of information we have, in principle, on these last group of stars, some of them could have been retained in our reference sample notwithstanding their being "peculiar".

4. Comparison between model results and observed EMSS source counts

In the following we will be comparing the predicted EMSS source counts both with the entire EMSS stellar coronal sample, and with the subsample of the EMSS from which objects classified as active binaries (RS CVn, W UMa, BY Dra and FK Coma type objects) by Fleming (1988) or Stocke et al. (1991) are not included in the comparison samples.

Table 3 shows the comparison between our model results and the observed stellar source counts for our EMSS subsample. The adopted coronal temperature (cf. Table 2) of old disk population stars are based on the results of the Einstein spectral survey (Schmitt et al. 1990). Notice that the assumed temperature varies with stellar age, as X-ray luminosity does. A non-parametric study of coronal spectra of a large stellar sample including Pleiades, Hyades and

[1] Some of the identifications originally proposed in Fleming's work has been revised by Stocke et al. (1991).

Table 3. Comparison of predicted X-ray counts for the EMSS sky coverage with observed counts

	Predicted Main Sequence Stars					
age (years)	A	F	G	K	M blue	M red
$10^7 - 10^8$	0.7 [0.6-0.8]	0.4[0.2-0.5]	2.3[2.0-2.7]	5.0 [4.4-5.8]	10.3 [9.8-11.0]	< 1
$10^8 - 10^9$	1.1 [0.9-1.4]	1.2 [0.9-1.6]	7.0 [6.4-7.8]	7.0 [6.4-7.7]	17.7 [16.5-19.0]	< 1
$> 10^9$	0.2 [0.1-1.6]	6.5 [4.7-9.5]	6.3 [4.7-9.6]	18.5 [14.0-25.1]	7.8 [6.7-8.9]	0.4 [0.3-0.4]
	Predicted Giant Stars					
–			0.6 [0.4-0.8]	0.2 [0.1-0.3]		
Total	2.0 [1.8-3.4]	8.1 [6.3-11.1]	16.2 [13.9-17.4]	30.7 [28.8-33.9]	35.8 [31.2-42.5]	~ 1
Observed: All[a]	9	26	43	52	27	4
Observed: MS+PMS	9	23	28	48	27	4
Observed: MS	7	23	28	44	24	4

The values between square brackets indicate the 16% and 84% range of predicted number counts. The values for the Total have been computed as the sum in quadrature of the errors of each of the three age components.
a - In this case we retained all the stars including those listed as RS CVn, W UMa-type, BY-Dra, FK Comae, or PMS stars either by Fleming (1988) or Stocke et al. (1991). Note that three stars having $B - V < 0$ do not appear in this table.

field stars has shown the hardening of stellar coronal emission with increasing stellar age (Micela, 1991). The result of this study is consistent with the observed relationship between X-ray luminosity level and coronal temperature (Vaiana 1983, Schmitt et al. 1990) found as a result of the parametric analysis of coronal spectra of the brightest sources.

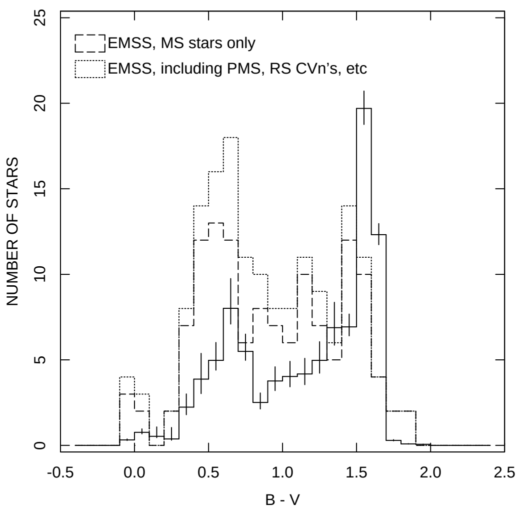

Fig. 2. Predicted distribution in $B - V$ for the EMSS superimposed to the observed one. The error bars on predictions are due to the uncertainties on the X-ray luminosity functions.

Figures 2, and 3 show the distributions of observed and predicted source counts for our EMSS sample, in $B - V$ and f_X/f_V. In Table 4 we have summarized the results of the statistical comparison between predicted number counts and observed number of normal main sequence EMSS stars (listed as the row labeled as "observed:MS" in Table 3). We have applied a standard χ^2 test (with one degree of freedom) to test for each of the stellar sample listed in Table 4 the null hypothesis that the observed and predicted number counts are drawn from the same parent population. In performing these tests we have accounted for errors both in predicted numbers and in observed ones. To account for the asymmetry in the allowed range of predicted numbers we have estimated the statistical significance of the results separately for the lower and upper range of values adopting the uncertainties on observed number according to the Poisson statistic. From this analysis the presence of an excess of observed F-G stars is evident. We will discuss its likely origin in the following.

4.1. Spectral types from A to early F ("white stars") and from late K to M ("red stars")

As clearly shown in Table 3 and in Figure 2 the number of predicted source counts is lower than the number of observed "white stars" (i.e. bluer than $B - V = 0.5$). We predict ~ 10 stars while the observations indicate that 30 of them have been detected. These two numbers are statistically different at 99.7% confidence level, as indicated in Table 4.

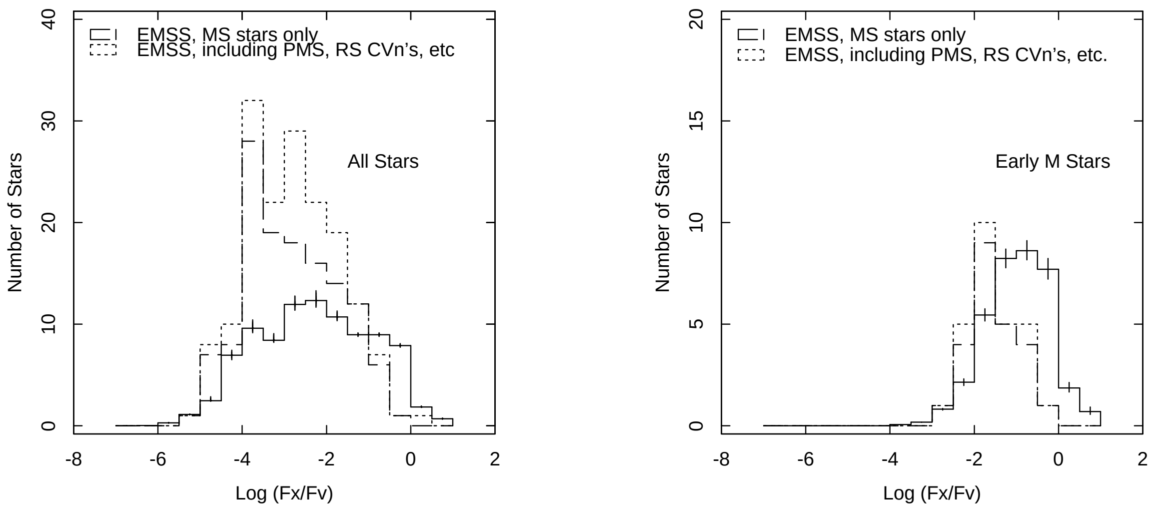

Fig. 3. Predicted distribution in f_X/f_V for EMSS superimposed to the observed one. The two panels show the results for the entire stellar sample, and for the early M stars respectively. The error bars on predictions are due to the uncertainties on the X-ray luminosity functions.

At the other extreme, namely for the "red stars" with $B-V > 1.45$, our calculation, based on the assumption of a constant stellar birthrate, predict $\sim$ 37 stars while 28 of them have been detected. The statistical significance of this result is marginal (confidence level $\sim$ 96-97%), moreover the fact that we predict only 1 very-low mass star while 4 of them have been observed should not be considered as a major discrepancy, since we presently have a poor knowledge of the X-ray luminosity functions of very-low mass stars of various coeval sample, as discussed for the case of old and young disk population stars by Barbera et al. (1993) and Fleming et al. (1993), for the case of the Pleiades by Stauffer et al. (1994) and Micela et al. (1993a,1994), and for the case of the Hyades by Stern et al. (1994).

A similar analysis of the results shown in Figure 3 indicates that we predict too many stars with log f_X/f_V greater than -0.5 belonging to the M star group.

These results suggest that the optical luminosity functions we have derived for the present work under-estimate the number of M stars hidden as companions in binary systems with an A/F type primary, at the same time over-estimating the number of single M stars. This would explain why we are unable to predict enough A/F stars with the high f_X/f_V observed in the EMSS. Such systems would naturally result from the presence of a X-ray active (unseen) M star companion of an A/F type primary. Indeed the predicted number of A, F, and M stars altogether is about 47 that compares reasonably well with the observed number of 58 altogether A, F and M stars.

This working hypothesis, however, does not explain why we predict too many M stars at very high f_X/f_V values. In this respect another possibility is that the identification process of Stocke et al.(1991) is biased against the recognition of M stars having f_X/f_V higher than usual.

Table 4. Summary of statistical analysis

Sp. Type	χ^2 Lower	Conf. Lev.	χ^2 Upper	Conf. Lev
A	3.93	95.257	1.82	82.269
F	12.18	99.952	6.13	98.671
G	6.55	98.951	2.51	88.687
K	7.43	99.359	1.06	69.678
M blue	4.25	96.075	7.75	97.463
A+F	15.77	99.993	9.13	99.749
F+G	16.76	99.996	9.60	99.805
G+K	12.67	99.963	4.39	96.385
K+M	0.64	57.629	0.40	47.291

4.2. Spectral types from F to early K ("yellow stars")

The comparison between our model predictions and the observed stellar source counts for yellow stars in the reference EMSS subsample shows a clear excess that peaks in the F-G spectral type range where the 70 observed sources have to be compared with the $\sim$ 24 predicted ones. This excess is statistically significant at more than 99.8% level.

From Figures 2 it can be seen that this excess is concentrated for $B-V$ ranging from 0.5 to 1.0 (corresponding to m_V ranging from 8 to 12) which corresponds, in the EMSS, to normal main sequence stars with spectral type comprised between F and early K. A similar conclusion can be drawn from the analysis of Figure 3 showing that the excess is concentrated for log f_X/f_V in the -4,-2 range. The excess seems to be spread over the entire m_V and f_X/f_V ranges typically populated by F, G and early K stars. This differentiates the behavior of the A/F stars from that of yellow stars.

4.3. Sensitivity of results to X-ray luminosity functions uncertainties

The statistical uncertainty associated with the X-ray luminosity functions is due to the small number of sources present in each sample. The uncertainty generated by the bootstrap process through which we account for unresolved binaries (cf. Appendix A) nevertheless dominates our final results, and it is therefore the one shown in the tables of integral source counts and in the distribution plots. We notice that predicted numbers are dominated by the bins at high luminosity of the X-ray luminosity functions. The exact shape of the tail is uncertain since it is derived from a small number of objects, while its overall shape (and existence), is unaffected by the censoring of the data.

4.4. Sensitivity to assumed stellar coronal emission models

We have studied the sensitivity of our results to variations in the assumed temperature of the X-ray emitting coronae. It is well known that there is a large variation of observed coronal temperature among stars of similar spectral type (in addition to the variation due to varying stellar age, as described above), and that the spectrum of some stars is better fitted by a two-temperatures spectrum (Schmitt et al., 1990). We have therefore performed model computations with assumed coronal temperatures spanning the range of commonly observed values (0.3-1.1 keV) and have concluded that the uncertainty due to the assumed source temperature is less than $\sim 10\%$, smaller than that due to the statistical error on the X-ray luminosity functions.

5. The yellow stars excess in the EMSS sample: likely explanations

The results presented above show a discrepancy between the observed source counts for yellow main sequence stars in the EMSS and the numbers that can be accounted for on the basis of *Einstein* X-ray luminosity functions: the observed source counts are consistently higher, for yellow stars, than the predicted values.

Such discrepancy had already been observed in the MSS sample by Favata et al. (1988), with a much lower statistical significance (due to the smaller number of sources detected in the MSS). On the basis of the higher statistical significance of the results presented here we consider this excess real, and most likely due to some high X-ray luminosity population with optical characteristics similar to normal main sequence yellow stars.

First we can rule out that the observed excess sources are normal giants: as it is evident from Table 3 the contribution of the disk population giants at the limiting sensitivity reached by the EMSS is negligible. No more than 1 normal giant star is expected to be detected in the overall EMSS. This calculation is based on the standard spatial distribution for the disk giants adopted in the Bahcall & Soneira model with a scale height of 250 pc, and an assumed coronal temperature of 1.1 keV, which, according to the Einstein stellar coronal spectra surveys (Schmitt et al., 1990) characterize the coronal spectra of X-ray detected giants. Since the predicted number of giant stars is about two order of magnitude smaller than that of main sequence stars, they cannot be considered as a viable explanation of observed excess.

We believe that the stellar population to which the "excess" yellow stars belong should be characterized by having a low spatial density and a high X-ray luminosity. Additionally, their optical appearance should be such that they are indistinguishable from normal main sequence stars on low resolution spectrograms. The two most likely classes of objects which correspond to this description are (i) active binary systems (RS CVn or W UMa like), (ii) very young active main sequence stars. The techniques used by Fleming (1988) in his extensive study of his EMSS subsample were very effective in the discovery of binary systems, so that very few undiscovered active binary systems should be hidden in his sample, although it is conceivable that some of them are still present. It seems unlikely then, within the framework of current knowledge, that the objects responsible for the excess counts could be mostly or only active binary systems. This can be substantiated by a detailed calculation of the expected number of RS CVn among detected coronal sources in the EMSS. A summary of various calculations is given in Table 5.

All these calculations have been performed assuming that the density of the RS CVn population at the Galactic plane is $1 \cdot 10^{-4}\mathrm{pc}^{-3}$, that they can be characterized by a coronal temperature of 1.1 keV, and using the X-ray luminosity function described in sec 3.4. As discussed by Ottman and Schmitt (1992) there is a clear disagreement between the properties of the X-ray and the optically selected sample of RS CVn, an area of major uncertainty being their space density. The current estimate based on optically selected sample ranges between $3 - 6 \cdot 10^{-6}$ and $1 \cdot 10^{-4}$ (Drake et al. 1989), while best estimate based on the EMSS indicate higher values (Fleming et al. 1989), that notwithstanding recent revisions (Fleming 1990, as reported by Ottman and Schmitt 1992) still are in the $2 - 3 \cdot 10^{-4}\mathrm{pc}^{-3}$ range.

Fleming et al. (1989) determine the space density of RS CVn from a sample of 12 objects. If some of the objects in their sample were mis-classified it is likely to expect that a small reduction of the sample size would decrease

Table 5. Predicted number of RS CVn in the EMSS

Scale Height pc	Predicted Number[a]
110	19.4 ± 7.1
250	39.4 ± 15.3
325	45.5 ± 17.8

a- All calculations assumed a space density in the Galactic plane equal to $1 \cdot 10^{-4}$. Listed number scale linearly with the space density.

significantly the resulting space density of RS-CVn's. In fact, Favata et al. (1993), in their analysis of the lithium abundance of the stellar content of the EMSS suggest that at least one of the objects originally considered by Fleming et al. (1989) as RS CVn, is a likely PMS star. Moreover Ottman and Schmitt (1992) have found that adopting $2-3 \cdot 10^{-4}\mathrm{pc}^{-3}$ as the space density of RS CVn they would predict a contribution to the excess X-ray Background in the Galactic Ridge even larger than the observed one, while a density of $1 \cdot 10^{-4}\mathrm{pc}^{-3}$ would explain half of the observed excess.

Based on all these arguments we consider that the space density of RS CVn's we have adopted (at the upper boundary of allowed values from optically selected sample) is likely to be an upper limit to true space density. This in turn implies that the predicted numbers listed in Table 5 should be considered as the *maximum* number of coronal sources that can be attributed to RS CVn population. Moreover we note that the number of active binaries detected in the EMSS is ~ 20. This number compares well with the result summarized in Table 5 (especially if we consider a more realistically reduced values for the RS CVn's space density). We have reported calculations for three distinct values of the RS CVn scale height. The lowest value has been reported by Hall (1976) on his early studies of RS CVn's properties, the highest value, that in our opinion is not a realistic one, is equal to the maximum values for disk population stars and has been adopted by Ottman and Schmitt (1992), while the intermediate value is that adopted in the Bahcall & Soneira model for the disk giant population stars. We have included it since in most RS CVn's one of the two components is often an evolved object, a subgiant or a giant. We conclude that a population of RS CVn's alone cannot explain the excess we have found.

The occurrence of very young active stars with high X-ray emission level, but without any grossly evident spectral peculiarity is well known (Feigelson et al. 1987; Walter et al. 1988, Damiani et al. 1994). It is therefore conceivable that such objects could have been classified as normal stars by Fleming (1988), while they are in fact the peculiar sources responsible for the excess counts in X-ray limited surveys. Such hypothesis cannot be tested through direct modifications of the X-Count model to include young active sources, as their spatial density is not well known and is thought in any case to be patchy, with concentrations close to star-formation regions, where the absorption is also patchy and therefore poorly known.

However, very young stars should have a high (close to primordial) lithium abundance, detectable by strong absorption in the Li 6707Å line which, while hardly evident in low or intermediate resolution spectroscopy, is a remarkable feature in high resolution spectrograms.

One of the goals of the observational work of Favata et al. (1993) was indeed to try to determine the nature of the yellow star excess. They have conducted an observational campaign of high resolution spectroscopic observations of the region around the LiI 6707 Åof the yellow stars of the EMSS. This work shows that the fraction of stars with a high lithium abundance in the EMSS subsample they have investigated is indeed much higher than what would be expected in a randomly selected sample. This result strongly indicates that the EMSS contains a high fraction of very young, active X-ray luminous stars. It is therefore very likely that the presence of such a population, not accounted for in the current Galaxy models as incorporated in our numerical code, could explain the observed excess of yellow stars in the EMSS. The existence of such a young stellar population at the high galactic latitude studied in the EMSS and far-away from known star formation regions is somewhat unexpected and certainly deserves further studies.

6. Summary and conclusions

We have performed a detailed comparison between the stellar content of the *Einstein* Extended Medium Sensitivity Survey and expectations computed on the basis of the current state of knowledge about stellar X-ray emission.

For red stars, we show that to reasonably match the observed source counts it is necessary to account for the effects of decreasing X-ray luminosity level with increasing stellar age as well as for the presence of X-ray unresolved binary systems. We find a marginally significant defect of M stars with high f_X/f_V ratio and argue that the identification process could be biased against this kind of X-ray active and optically faint stellar objects.

We found an excess for the A/F star groups mainly due to the occurrence of stars with f_X/f_V ratio higher than the mean values for each group and suggest that this could be explained by the occurrence of a larger number of X-ray unresolved binary systems with an active M star companion than the predicted ones. These systems would preferably be selected by a flux-limited X-ray survey.

For yellow stars, the current state-of-art knowledge in terms of X-ray luminosity functions is not able to account for all of the observed yellow stellar sources in the EMSS, so that, to explain the observed source counts, a new population of stellar-like X-ray emitting sources with optical characteristics similar to normal main sequence yellow stars must be hypothesized. We have shown that, based on current knowledge, this population is likely to be (at least partly) composed of very young (and therefore highly X-ray luminous) yellow stars, perhaps of the kind variously indicated by previous authors as WTTS or NTTS, or simply by near ZAMS objects. While very young stellar objects have been since long been identified as strong X-ray sources, they have not so far been indicated as major contributors to global X-ray source counts.

We have further shown that the problem of studying in detail the stellar content of an X-ray flux limited survey, especially with detectors of limited spatial resolution such as the *Einstein* IPC, the ROSAT PSPC, and the future XMM EPIC, is a quite complex issue. While the methodology we have developed and adopted in our work could be considered too involved and complex given the limited quality of the data (i.e. the EMSS stellar content) available at the present moment, still the proposed approach can be easily directly applied to the case of other X-ray flux limited surveys such as that recently concluded with ROSAT and that foreseen with XMM and AXAF where we expect to obtain data of substantially better quality.

Appendix A

Here we give further details on the determination of optical and X-ray luminosity function that account for the occurrence of binary systems. Adopting the mass-luminosity relation given by Rana (1990) and a mean ratio of secondary to primary star masses equal to 0.5 (cf. the discussion in sec. 2.1 of Basu and Rana, 1992) we have computed the optical luminosity function of *individual* stars assuming a fraction of binary systems of 0.5. Given the uncertainty in derived luminosity functions above $M_{\rm V} = 15$ (Stobie, Ishida, and Peacock 1989), we have restricted ourselves to $M_{\rm V} \leq 15$. Assuming a constant stellar birthrate, a main-sequence life-time, τ_{ms}, as function of the mass according to Basu & Rana (1992), and a Galactic disk age of 12×10^9 yr we have computed the optical luminosity functions of combined single and binary systems in three distinct age ranges.

Based on the optical luminosity functions of *individual* stars we have generated through a bootstrap procedure 200 samples of 1000 stellar systems each, with a fraction of binary systems equal to 50% of the total number of stellar systems, and neglecting any triple or multiple system. In generating binary systems we have assumed that the probability of their formation is independent on stellar mass. As a final step we have computed the X-ray luminosity for the resulting single and binary stars, assigning with a bootstrap procedure an X-ray luminosity values to each individual star, adding up the optical and X-ray luminosities in the case of binary systems and assigning each binary system to the color interval corresponding to the resulting combined absolute magnitude. With this procedure we have computed for each given set of X-ray luminosities the median and the 16% and 84% quantiles of the resulting 200 X-ray luminosity functions we have generated. The resulting median, 16% and 84% quantiles X-ray luminosity functions have been then adopted in our calculations.

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