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The stellar coronal component of the Galaxy

I. The X-COUNT numerical model

F. Favata[1], **G. Micela**[2], **S. Sciortino**[2], **and G. S. Vaiana**[2*]

[1] Space Science Department - ESA/ESTEC, Postbus 299, NL-2200 AG Noordwijk, Nederlands
[2] Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy

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Abstract. We present a computational model for the prediction and analysis of the distribution of galactic X-ray stellar coronal source counts, based on models for the distribution of stars and of interstellar hydrogen in the Galaxy and on known properties of stellar X-ray emission in the solar neighborhood. The model can be, and has been used, for comparisons with unbiased X-ray surveys (equivalent to the deep source counts conducted in the optical), for predictions of stellar X-ray observations with new instruments and to estimate the stellar contribution to the X-ray background.

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

1. Introduction

Optical stellar source counts down to faint limiting magnitudes, in selected directions in the sky, have since long constituted a powerful method for probing the structure and the distribution of stars in the Galaxy (Mihalas & Binney, 1981; Bahcall, 1986; Gilmore et al., 1989, and references therein cited). Such source counts, when compared with the results predicted by computational models of the Galaxy, such as the Bahcall & Soneira model (Bahcall & Soneira, 1980), the Gilmore model (Gilmore, 1984) or the Robin & Crézé model (Robin & Crézé, 1986), constitute the ultimate observational test for such models. This approach has given us confidence in the general correctness of our current ideas about the basic characteristics of the stellar components of our Galaxy, such as the spatial distribution, the relative abundance of stars of different mass and the relationship between color and magnitude.

The study of coronal X-ray emission from normal stars, on the other hand, has been most often conducted following one of two approaches. The first one consists of studying volume limited samples of optically selected stars with the main goal of determining the distributions of X-ray luminosities within a single spectral class, the so called X-ray luminosity function (Schmitt et al., 1985; Micela et al., 1985; Maggio et al, 1987; Micela et al., 1988; Feigelson & Kriss, 1989; Damiani et al., 1990; Maggio et al., 1990; Micela et al., 1990; Schmitt et al., 1990a; Barbera, 1991; Barbera et al., 1991). The second approach consists in studying the optical counterparts of sources detected in unbiased X-ray surveys, with the main goal of selecting unbiased samples of X-ray emitting objects, as done, for example within the *Einstein* Extended Medium Sensitivity Survey (EMSS) (Gioia et al., 1990; Stocke et al., 1991), the *EXOSAT* High Latitude Galactic Survey (Giommi et al., 1991), or the study of star forming regions (Feigelson et al., 1987; Strom et al., 1990).

Since the discovery, made by the *Einstein* Observatory in the early 80's (Vaiana et al., 1981) that most normal stars are soft X-ray sources, studies following the first of the above mentioned approaches have been extensively carried forward to establish a coherent and comprensive picture of the characteristics and the underlying mechanisms of stellar X-ray emission. While these studies have so far supplied most of our current knowledge about stellar X-ray emission (Rosner et al., 1985; Vaiana & Sciortino, 1987; Vaiana, 1990, and and references therein), they leave most of the information present in unbiased surveys of X-ray sources (such as observations of stars not included in the pre-defined samples) unused.

Unbiased X-ray surveys are conceptually equivalent to optical stellar source counts, and contain a large amount of information regarding the nature and the characteristics of the observed stellar population. The content of such surveys can be studied by identifying the optical counterparts of each individual source and studying its characteristics individually. Such an approach has been already taken studying the stellar data of the EMSS and has allowed to identify a complete sample of x-ray selected stars (Fleming, 1988; Stocke et al., 1991). Among these stars have been identified 12 new candidates for the RS CVn class and 7 new candidates for the W Uma class (Fleming et al., 1989a). No M dwarfs later than M5 have been detected, and the majority of detected M dwarfs are emission line stars (Fleming et al., 1988). The analysis of the late-type stars detected in the EMSS confirms the $L_x, v \sin i$ correlation for single stars, however the lack of correlation between L_x and $\Omega \sin i$ has been interpreted as providing plausible evidence for saturated levels of stellar coronal activity (Fleming et al., 1989b).

It is also possible to study a survey's content by developing a detailed model of the distribution and characteristics of the emitting sources. When compared with the observational data derived from unbiased X-ray surveys such a model allows

Send offprint requests to: F. Favata

*After this paper had been submitted, G. S. Vaiana died untimely on Aug. 25, 1991.

to make use of all the information contained in the surveys in the form of serendipitous sources regardless of their distance. Such an approach provides a different perspective on the ubiquitous phenomenon of coronal X-ray emission, and, applied to the stellar data of the *Einstein* Medium Sensitivity Survey (Gioia et al., 1984), and of the *Einstein* Hyades Region Survey (Micela et al., 1988) has already allowed to identify the existence of a class of X-ray luminous "yellow" stellar objects which contributes significantly to the stellar log N-log S distribution. These objects cannot be reconcilied with normal G and K main-sequence stars, and were tentatively identified with active, RS-CVn-like binaries or young active stars (Favata et al., 1988). Moreover the analysis of X-ray flux surveys in regions of star formation has demonstrated the existence of a class of pre-main sequence stars revelead through their intense coronal emission (Montmerle et al., 1983; Feigelson et al., 1987; Walter et al., 1988).

To investigate this problem, and following the "modellistic" approach, we have developed a computational model to predict the expected number of coronal sources of each spectral type in a X-ray observation of given area and limiting sensitivity. We expect this model to give a realistic description of X-ray stellar coronal source number counts for any direction with the exception of "special" regions, such as for example star formation regions rich of active X-ray emitting Pre Main Sequence (PMS) stars. The model is based on the current best knowledge about galactic structure, distribution of stars and properties of stellar X-ray emission. In the present paper we present the model itself, the underlying physical assumptions (sec. 2), its computational structure (sec. 3), and some examples of possible applications (sec. 4).

2. Model characteristics

The computation of the number of stellar sources expected in a given X-ray observation is in principle a simple operation: such a number is the integral of the stellar density in the volume of space observed, given source luminosities and limiting sensitivities of observations. The basic operations to be performed by the model are therefore the computation of the integration limit (the maximum distance at which sources are seen for a given limiting flux) and the actual integration itself. While conceptually simple, such operations involve a number of assumptions, and the algorithms used have to be adapted to the desired output. In what follows each assumption used in the model will be discussed, and the algorithms used for the computation will be described.

Not all the physical parameters used in the model are known with the same degree of certainty: the present knowledge of the spatial distribution of normal main sequence and giant stars in the Galaxy has well known uncertainty areas, such as the number density of very bright or very faint stars and the still disputed existence of a population of giant stars with a scale height of a few kpc (Gilmore & Reid, 1983; Norris, 1987). At the same time the determination of the volume of space visible in each single observation involves uncertain factors such as the distribution of X-ray absorbing material in the Galaxy, the way in which X-rays are absorbed, the spectrum of the emitted X-rays and the sensitivity of the detector used in performing the observations.

The influence of each of those relatively uncertain elements on the final results needs to be explored separately by performing several numerical experiments to assess the sensitivity of final results on input physical assumptions.

2.1. Physical assumptions

The main elements needed to compute the distribution of X-ray source counts in a given field, observed with a given detector at a given limiting sensitivity, are the following:

1. The spatial distribution and the density of the sources.
2. The distribution of X-ray luminosities for the given source type (e.g. its X-ray luminosity function).
3. The density of absorbing material along the line of sight.
4. The spectrum of X-ray emitting plasma.
5. The instrumental response of the given X-ray detector.
6. The color-magnitude relationship of the sources (only if the computation of the predicted color distribution is required).

Each of the above elements and the associated model assumptions is described in detail in the following.

2.1.1. Density and distribution of stars

The density of normal stars as a function of the position in the Galaxy and of absolute magnitude is one of the main components of any Galaxy model, and we have adopted the published spatial densities of the Bahcall & Soneira model (Bahcall & Soneira, 1980; Bahcall, 1986). Given the effectiveness of this model in predicting optical source counts the stellar luminosity function[1] is considered to be known, for the classes of sources included, with a good amount of confidence. In our present version of the model we have considered only the disk component, comprising both main sequence and giant stars. For the range of X-ray fluxes for which we have so far tested the model, the contribution of giant stars to X-ray star counts has shown to be negligible relative to the contribution of main sequence stars. The halo or spheroid component is not currently accounted for: this choice reflects our present limited knowledge of X-ray emission of spheroid stars. However halo stars, because of their low density in the solar neighborhood should not significantly contribute to X-ray counts, at least in the range of X-ray fluxes covered by *Einstein*, *EXOSAT*, and *ROSAT* observations. Furthermore, because of their old age, they are likely intrinsically faint X-ray emitters, a prediction that is not contradicted by the most recent survey of X-ray emission of low mass stars (Barbera, 1991; Barbera et al., 1991).

For working with sources which are important X-ray emitters but which are not important contributors to optical source counts (and thus not taken into account in the Bahcall & Soneira model), and which are considered to be spatially distributed similarly to normal disk population stars, but with an usually lower spatial density (such as active binaries) we have included the possibility of describing the spatial distribution of sources as an external input parameter, by specifying the scale height and the density on the Galactic Plane. This is useful, for example, for

[1]The term *luminosity function* is used with two different meanings by X-ray astronomers and by the optical astronomers. While for the latter the stellar luminosity functions in a given point of the Galaxy is the absolute stellar density, in stars per cubic parsec, as a function of absolute magnitude, for X-ray astronomers the X-ray luminosity function for a given stellar class is the distribution (usually expressed in integral form) of X-ray luminosities for the stars in the given class.

computing the contribution of *RS CVn* type stars to the global X-ray source counts. To use this option an indipendent knowledge of the spatial distribution and density of the population must be assumed. This can be derived, for example, from indipendent surveys in various wavelenghts (optical, radio, etc.). Our model (as the original Bahcall & Soneira Galaxy model) does not currently account for classes of X-ray sources which are distributed in a "patchy" way, such as early type stars (likely to be concentrated in associations) or PMS stars (likely to be concentrated in star forming regions).

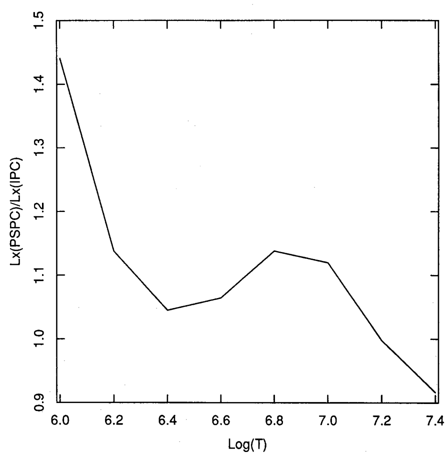

Fig. 1. Ratio between the flux detected by the *ROSAT* PSPC and the *Einstein* IPC for a hot, optically thin single temperature plasma (Landini & Monsignori-Fossi, 1990) as a function of temperature

2.1.2. X-ray luminosity functions

For all our work with the model we have used X-ray luminosity functions derived from published *Einstein* IPC data (Schmitt et al., 1985; Maggio et al., 1987; Micela et al., 1988; Feigelson & Kriss, 1989; Micela et al., 1990; Maggio et al. 1990; Damiani et al., 1990; Barbera, 1991) in the (0.16 - 4.0) keV energy range. These X-ray luminosity functions, obtained from samples of stars in the solar neighborhood, are maximum likelihood X-ray luminosity functions because some of the stars have not been detected in the X-ray and therefore only an upper limit to their X-ray luminosity is known. For this reason techniques developed for analysis with censored data (Avni et al., 1980; Schmitt, 1985; Feigelson & Nelson, 1985) have been used. The X-ray luminosity functions are specified in differential form, and subdivision among stellar spectral classes is done on the basis of the $B-V$ color, a more easily measured quantity than spectral type.

The X-ray luminosity functions deduced from *Einstein* observations constitute the best information available up to date. While they can be rigorously used for computing expected source counts in observations done with the *Einstein* IPC detector (0.16-4.0 keV), their information content can be extrapolated, assuming a given input spectrum, in slightly different energy passbands such as that of the *EXOSAT* CMA (0.05-2.0 keV) or *ROSAT* PSPC (0.1-2.0 keV). In Figure 1 we show as a function of temperature the computed ratio between the *ROSAT* PSPC flux and the *Einstein* IPC flux for an optically thin plasma whose emission has been described adopting the Landini and Monsignori-Fossi (Landini & Monsignori-Fossi, 1990) spectrum. The adopted spectrum is well suited to describe the X-ray and EUV emission from a plasma with physical conditions such as those in stellar coronae. It is quite evident that for the range of coronal temperatures typical of stellar coronae (Schmitt et al., 1987; Pallavicini et al., 1988; Schmitt et al., 1990b) the correction for the change of bandpass is less than 30%. The uncertainty on this correction is smaller than uncertainties on X-ray luminosities determined with the *Einstein* IPC due to statistical and systematic effects.

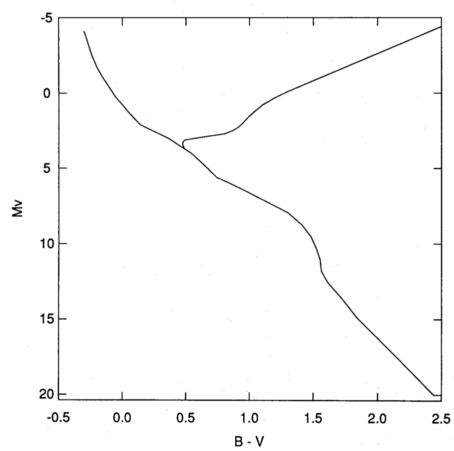

Fig. 2 Relationship between color and magnitude for disk population stars, given in the Bahcall & Soneira model (Bahcall & Soneira 1980), adopted in present work

2.1.3. Color-magnitude diagram

The relationship between color and magnitude is taken from the Bahcall & Soneira model (to which we refer the reader for further references) and it is shown in Fig. 2. It is specified in the form of a set of points, which are interpolated with a cubic spline to obtain values not explicitly tabulated.

2.1.4. Age of sources

X-ray luminosity varies considerably, in the case of late type main sequence stars, with source age (Vaiana, 1983; Micela et al., 1985; Micela et al., 1988; Feigelson & Kriss, 1989; Micela et al., 1990), with the youngest objects being the stronger emitters. The model can compute separate source count contributions for young and old objects among late-type (G, K, and M) dwarfs. To do this both X-ray luminosity functions and spatial densities must be specified separately for young and old objects.

The scale height of disk population stars increases with age (Mihalas & Binney, 1981), and therefore massive stars have scale height smaller than late type stars which have a greater average age. From the point of view of optical counts, if we assume a constant stellar birth-rate, the population of late type stars is dominated by old stars (age greater than 10^9years) and, as the optical luminosity does not vary significantly with age, the average scale height of late type stars is the one appropriate for old stars of the appropriate spectral type. From the point of view of X-ray counts, due to the large age dependence of stellar X-ray luminosity, the difference in spatial distribution between young and old objects leads to effects evident in observations at typical *Einstein* sensitivities, because the young, X-ray bright stars tend to be substantial contributors to observed source counts for their spectral class.

For these reasons we have modified the spatial distribution of the Bahcall & Soneira model to take into account, to first order, the age effect in the space distribution of late type stars. If we subdivide late type stars into two age components, with young disk stars having a scale height reduced by a factor of two relatively to old disk stars of the same spectral type, and with a density on the Galactic plane equivalent to 10% of the total density for the appropriate spectral type, the obtained optical star counts are in agreement within 5% with those obtained with standard Bahcall & Soneira model, i.e. the results of the modified version of the model are essentially as good as the original ones when compared with available experimental data (cf. the spread in measurements in Fig. 2 of Bahcall, 1986) and the same holds considering the color distributions.

On the the other hand predicted X-ray counts can change up to a factor of three, depending on the latitude. The value of 10% chosen in the example for the density of young stars is a typical value; results are similar for values of density for the young stars comprised between 5% and 20%. Table 1 shows a comparison between the optical star counts predicted by the original Bahcall & Soneira model and the ones predicted by our modified version at various limiting magnitudes, while table 2 shows a similar comparison for the predicted X-ray source counts at various X-ray limiting fluxes. It follows that X-ray counts are a more powerful diagnostic than optical counts for the relative density and scale height of young and old disk population stars.

2.1.5. Interstellar absorption

Soft X-rays are absorbed in the Galaxy mainly by heavy elements present in the interstellar gas; their presence can be estimated, assuming cosmic abundance, by the amount of atomic hydrogen along the line of sight between the source and the observer. The code uses the model of galactic hydrogen distribution obtained from radio observations of Lockman (Lockman, 1984), which models the interstellar hydrogen distribution as function of the distance from the galactic plane in the following way:

$$n(z) = 0.1586 \times e^{(-((z-3)/212)^2)} + 0.0926 \times e^{(-((z+84)/508)^2)} + 0.0527 \times e^{(-|z+26|/480)}, \quad (1)$$

where z is in parsec and n is in cm^{-3}. This model has been shown by its author to be in good agreement with observed interstellar absorption in the UV.

The absorption of X-rays is energy dependent, the end effect being that source intensity is reduced and source spectra are hardened by interstellar absorption. When the detector used has a sensitivity which is also energy dependent (as in the case of proportional counters) the effect of the absorption on the observed flux needs to be computed taking into account both the emitted source spectrum and the detector spectral response as explained in detail in section 2.1.6.

2.1.6. Characteristics of instruments

The relationship between detector specific flux units (counts/second) and absolute flux units (erg cm^{-2} sec^{-1}) depends, in the case of X-ray imaging detectors, on many parameters, such as source spectrum, absorption (see above), and position within the field of view.

The model assumes the limiting sensitivity of an observation to be specified in detector units and converts it to unabsorbed incident flux (in erg cm^{-2} sec^{-1}) using a calibration data table that it is read at run time (cf. sec. 3.3). Different instruments are specified by distinct calibration data tables. Such calibration data tables consist of conversion factors between observed X-ray fluxes in instrumental units (counts/sec, which are affected by absorption and instrumental response) and emitted X-ray fluxes in physical units "at the source" (i.e. before absorption and folding with the instrumental response). The conversion factors are tabulated for different values of interstellar hydrogen column density and source spectral temperature. The computation of such table requires an assumed source spectrum and absorption model and detailed knowledge of the detector response. For X-ray detectors used on "observatory-type" X-ray missions such calibration data are usually supplied, for a range of model source spectra, with the data (see for example Harnden et al., 1984; Harris et al., 1990), and can be used as they are in the model. For the purposes of our model we have in all cases adopted calibration data for a Raymond type spectrum from a hot plasma with solar abundances, typical of stellar coronae (Raymond & Smith, 1977).

The variation of sensitivity across the field of view is not explicitly taken into account, but the effect can be (and has been) compensated by sub-dividing the field to be analyzed in areas of homogeneous limiting sensitivity. For example, in the case of *Einstein* IPC observations, a subdivision in 4 areas of almost homogeneous sensitivity is sufficient, and further subdivisions do not significantly increase the precision of the calculation.

3. Code implementation

3.1. Code requirements

A preliminary, more rudimentary version of this code had been coded in FORTRAN 66 on a PDP-11 machine (Favata et al., 1988), and it had proven very hard to modify to get the required flexibility. So, when a major revision of the code was in order, it has been decided to rewrite it completely in standard ANSI C. To allow for the required capability of performing different numerical experiment to explore a large parameter space the model has been designed to maintain a great level of flexibility and a reasonably friendly user interface, while maintaining considerable speed and accuracy in computation. Moreover the structure of the C code which constitutes the model is modular, and it is divided into three parts: a user interface shell, a package of utility functions, and a library of self-contained routines which perform the desired integration. The inner working of those routines depends strongly on the type of integration required.

Model design and preliminary implementation, dating back to 1988, were originally developed at Osservatorio Astronomico di Palermo on a Unix-like platform, while final implementation, testing, and debugging were performed both at ESTEC and at Osservatorio Astronomico di Palermo in the last year. The code has been run and tested on several platforms, and its design makes it easy to port it to other, not yet supported, platforms, which are only required to support an ANSI standard C compiler. The current version has explicit support (through compile-time switches) for Ultrix, SunOS, VAX/VMS, Macintosh and MS-DOS operating systems.

3.1.1. Flexibility

The model has been designed so that every physical and computational parameter can be set independently, allowing easy

Table 1. Comparison of predicted optical star counts (number of stars per square degree) at $l = 0°$ between the original (*BS*) and our modified version (*MBS*) of the Bahcall & Soneira model for two distinct values of density (ρ a z=0) of young K and M dwarf stars in the Galactic Plane.

	b = 10°			b = 30°			b = 90°		
m_V	*BS*	*MBS* $\rho_y = 0.1\rho_o$	*MBS* $\rho_y = 0.2\rho_o$	*BS*	*MBS* $\rho_y = 0.1\rho_o$	*MBS* $\rho_y = 0.2\rho_o$	*BS*	*MBS* $\rho_y = 0.1\rho_o$	*MBS* $\rho_y = 0.2\rho_o$
12	101.2	101.2	101.2	40.1	40.1	40.1	14.8	14.8	14.8
13	256.7	256.7	256.7	85.4	85.4	85.3	29.5	29.4	29.3
14	620.1	620.0	619.9	175.8	175.5	175.1	56.3	55.9	55.4
15	1422.4	1421.8	1421.3	352.0	350.5	348.9	100.3	98.7	97.1
16	3104.7	3102.2	3099.7	682.0	675.5	669.0	162.5	158.0	153.6
17	6524.3	6513.1	6501.9	1241.8	1219.7	1197.7	239.3	229.7	220.2
20	58373.9	57576.3	56778.8	4306.0	4077.3	3848.6	613.6	574.3	534.9

Table 2. Comparison of predicted X-ray stellar source counts (number of stars per square degree) with B-V > 0, at $l = 0$, as a function of limiting X-ray flux, evaluated for the original (*BS*) and the modified version (*MBS*) of the spatial distribution of stars of the Bahcall & Soneira model for two distinct values of density (ρ a z=0) of young K and M dwarf stars in the Galactic Plane.

	b = 10°			b = 30°			b = 90°		
Log(F_x) erg $cm^{-2}s^{-1}$	*BS*	*MBS* $\rho_y = 0.1\rho_o$	*MBS* $\rho_y = 0.2\rho_o$	*BS*	*MBS* $\rho_y = 0.1\rho_o$	*MBS* $\rho_y = 0.2\rho_o$	*BS*	*MBS* $\rho_y = 0.1\rho_o$	*MBS* $\rho_y = 0.2\rho_o$
-12.0	0.03	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02
-12.5	0.13	0.07	0.09	0.13	0.07	0.08	0.12	0.06	0.07
-13.0	0.67	0.38	0.44	0.62	0.35	0.40	0.55	0.30	0.34
-13.5	3.3	1.8	2.1	2.9	1.6	1.8	2.4	1.3	1.4
-14.0	15.5	8.7	10.0	13.0	7.0	7.8	9.6	5.0	5.5
-14.5	69.5	38.5	43.8	54.2	28.3	31.1	33.6	17.2	18.1
-15.0	297.0	161.1	180.8	204.9	103.9	110.8	97.2	50.1	51.0

experimenting. Fundamental parameter are not hard-coded in the source code but are read at run time from configuration files or from keyboard input. Suitable default values are present in the code for parameters not properly initialized at run time, thus preventing erroneous results.

3.1.2. User interface

To make the code flexible for the end user an interactive user interface has been designed in the code from the outset. At the same time the portability requirement has limited the user interface to a standard "glass teletype", line by line, mode. The model comprises a simple, line oriented command language, which allows the user to set all the model parameters during execution, with no need to access source code. The command language is self contained in a separate source module, and it easy to add new commands to it, for the addition of new functionality to the code. Presently about 40 distinct commands are supported.

3.2. Possible computations

The predicted source content of a given X-ray observation can be computed in several different ways (see below). The model code includes several different modules, one for each type of computation.

3.2.1. Integral source counts

The simplest possible computation gives as a result the total number of sources of a certain type expected in a given observation at a given limiting sensitivity, such as, for example, the number of main sequence stars in a given B-V range expected in a given *Einstein* IPC observation. While providing only integral information, this type of computation can be optimized to run faster than more detailed ones. A typical run, for a given direction, a limiting flux of 10^{-13}erg sec^{-1} cm^{-2}, and an X-ray luminosity function with about 30 bins, takes about 0.8 sec of cpu time on a DEC™ 5500.

3.2.2. Log N(>S)-log S

This option computes the number of sources of given type observed for a given sky direction up to a given limiting sensitivity, in erg sec^{-1} cm^{-2}, as a function of the sensitivity itself. A typical run, for a given direction, in the range of flux from 10^{-13} up to 10^{-17}erg sec^{-1} cm^{-2} subdivided in 20 steps, and an X-ray luminosity function with about 30 bins, takes about 19 sec of cpu time on a DEC™ 5500.

3.2.3. Stellar contribution to X-ray background

This option computes the predicted background intensity, in instrumental unit (counts $s^{-1}arcmin^{-2}$), due to undetected stellar sources of a given type toward a chosen sky direction observed with a given limiting sensitivity, expressed in instrumental unit. This option has been implemented for a more direct comparison with experimental data on the soft X-ray background (Micela et al., 1991), and produces output directly in instrumental units. A typical run, on a DEC™ 5500, takes about 3 sec of cpu time for a given direction, a limiting flux of 10^{-13}erg sec^{-1} cm^{-2}, and an X-ray luminosity function with about 30 bins. The calculation time increases rapidly with the number of bins of the X-ray luminosity functions in the low X-ray luminosity range.

3.2.4. Distributions: m_V, $B-V$, f_X/f_V

This option allows the break-down of the predicted source count in a given observation as a two-dimensional distribution in two of the three quantities m_V, $B-V$, f_X/f_V. While providing far more information than the computation of integral source counts, this option is much more computationally intensive. On a DEC™ 5500, for a given direction, a limiting flux of 10^{-13} erg sec^{-1} cm^{-2}, and an X-ray luminosity function with about 30 bins the (m_V, $B-V$) and the (m_V, f_X/f_V) distributions take about 1 sec and about 2 sec of cpu time, respectively. Other distribution such as in M_V, L_X, f_X can be obtained with a proper use of the model.

It is noteworthy that all the above calculation can be repeated on a grid of input directions to obtain a complete description of predicted distributions of X-ray stellar counts and/or stellar contribution to the X-ray background on the whole sky. The design of the code, including well separated modules, allows to easily extend the possible computations than can be performed.

3.3. Structure of inputs

Complex inputs, such as calibration files, color magnitudes diagrams and X-ray luminosity functions are stored in ASCII files, whose name must be provided to the model at run time, while simpler inputs, such as the spectral class of the sources, can be supplied interactively from the keyboard. A facility is provided to read a sequence of commands from a file rather than from the terminal, allowing easy set-up of frequently used input command sets.

All the files used by the code, both for input and output, are ASCII files. Currently, we have included in the model the proper calibration data for the *Einstein* IPC detector (Harnden et al., 1984; Harris et al., 1990) and for the *ROSAT* PSPC (*ROSAT*-Observatory, 1991) for Raymond spectra from a hot plasma with solar abundances[2]. The calibration data are tabulated for 7 different source temperatures (kT ranging from 0.01 keV to 10.0 keV) and 10 different hydrogen column density (from $3\times10^{18}cm^{-2}$ to $10^{23}cm^{-2}$). Bi-linear interpolation is performed for temperatures and H column densities not explicitly tabulated.

To adapt the model to a different instrument/mission an appropriate detector calibration file must be provided, and the X-ray luminosity functions must be scaled to the different energy passband of the new instrument.

[2]Such spectra are appropriate for coronal sources.

3.4. Determination of the maximum observable distance

To perform the integration of the stellar density it is first necessary to determine the maximum integration distance, taking into account the source luminosity, the observation limiting sensitivity and the absorption along the line of sight. This is done as follows:

- The limiting flux f_X for the given observation is computed from the limiting sensitivity given in input (in counts/second), using the table described in section 2.1.6 and assuming no absorption is present.
- The maximum distance at which the source might be visible, still ignoring absorption, is computed, using the geometrical relation $d_{max} = \sqrt{L_X/(4\pi f_X)}$
- The actual maximum distance at which the source can be observed is computed by solving numerically in d the equation $f_X = \frac{L_X}{4\pi d^2}\text{absorb}(n_H(d))$ where $n_H(d) = \int_0^d \rho_{n_H}(r)dr$ is the integrated hydrogen column density up to the distance d, and absorb(n_H) is the factor by which the X-ray flux is reduced by a given hydrogen column density. This factor depends strongly on both the source spectrum and the instrument's bandpass, and has no simple analytical form. Therefore it is computed using the tabulated data of detector calibration described in sec. 2.1.6. The absorption factor is computed by taking ratio between the tabulated conversion coefficients and the coefficients at $n_H = 0$, and interpolating bilinearly to find the absorption value at an arbitrary value of kT and n_H within the table range. The interpolation in kT is done only once at the beginning of the computation (when the source temperature is specified), while the interpolation in n_H is done whenever needed. To solve the above equation numerically a simple bisection method is used, searching for solutions between $d = 0$ and $d = d_{max}$. This is possible because the function $f_X(d)$ is monotonical.

3.5. Integration methods

Once the maximum distance d is determined, the model computes the expected source counts down to the given limiting sensitivity by computing the following integral:

$$n = \frac{4\pi}{41,235}a \times \int_0^d \int_{L_{X\min}}^{L_{X\max}} \int_{M_{V\min}}^{M_{V\max}} \rho(M_V, l, b, r) f(L_X) dM_V dL_X r^2 dr, \quad (2)$$

where 41,235 is the number of sq. degrees is the sky, a is the area (in sq. degrees) of the field under analysis, $f(L_X)$ the X-ray luminosity function, l and b are the galactic coordinates of the field, $\rho(M_V, l, b, r)$ is the stellar density function for the spectral type under study (its spatial density), $M_{V\min}$ and $M_{V\max}$ are the lowest and highest absolute magnitudes comprising the stellar type under study and $L_{X\min}$ and $L_{X\max}$ are the highest and lowest

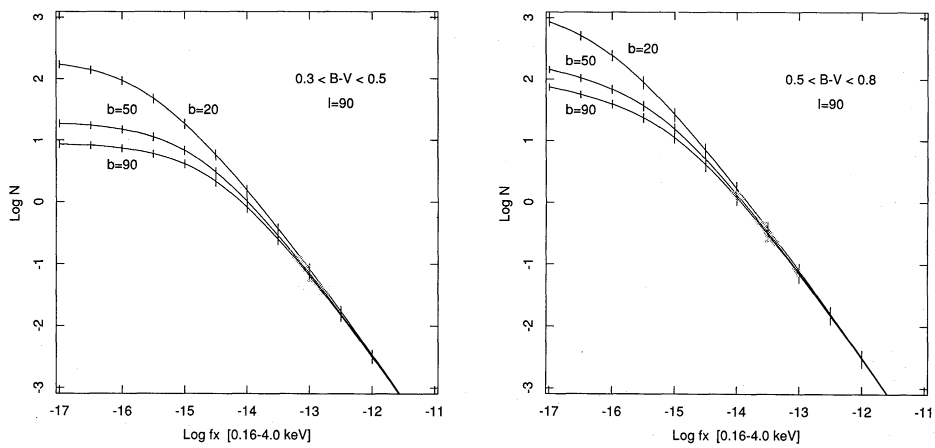

Fig. 3 Predicted 0.16-4.0 keV log $N(>S)-\log S$ diagrams for main sequence stars: (a) [left panel] in the $0.3 < B-V < 0.5$ range (late-A, early-F) and (b) [right panel] in the $0.5 < B-V < 0.8$ range (late F-G), at various galactic latitudes, for a value of galactic longitude of 90°. For all computation a coronal temperature of 0.3 keV has been assumed. Typical error bars are shown

values of X-ray luminosities for which the X-ray luminosity function is defined.

When integral source counts are required, the above integration is performed by doing a 10 points gaussian integration in M_V and a Romberg integration in r (Press et al., 1987). The integration in L_X is performed by simply adding up the contribution of each bin in the X-ray luminosity function.

When the computation of a distribution is required, it is not possible to use the above integration methods, as each element in the M_V, r, L_X space will contribute with different values of m_V, $B-V$, f_X/f_V to the total source counts. In such a case the computation is performed using a simple rectangular integration, with fixed integration steps (supplied as input parameters) and accumulating the contributions from each volume element in a matrix whose coordinates are two of the three quantities m_V, $B-V$, f_X/f_V creating a distribution.

The use of such a rudimentary integration decreases the speed but with a sufficient number of steps the precision is little affected.

3.6. *Accuracy of predictions*

The most uncertain elements of the model are the X-ray luminosity functions which are computed starting from a limited sample of objects and therefore have associated a relatively large statistical error. Provisions are made in the model for the propagation of the statistical errors associated with the X-ray luminosity functions onto the model results. Typical values for the relative error on the predicted source counts are in the range 15-30%, typical error bars are shown in figure 3.

From the computational point of view, the uncertainties associated with the X-ray luminosity functions are simply propagated along the various steps in the computation. Given that the uncertainties associated with the X-ray luminosity functions are much larger than the discrepancy between observed and predicted optical source counts in the Bahcall & Soneira Galaxy model, no provision is made in the model to account for uncertainties on the spatial density and distribution of sources. Furthermore, the uncertainty associated with interstellar hydrogen column density is not accounted for in the model. The model of interstellar hydrogen distribution used in our model has been shown to be quite accurate on the average (Lockman, 1984), although it models neither patchness nor interstellar clouds. Thus, we stress that the results of our model are valid from a statistical point of view, and are not necessarily valid in a given direction of peculiar absorption.

3.7. *Implementation of age subdivision*

To separately compute the contributions of the old and young sub-populations of late type main sequence sources, using two or more different X-ray luminosity functions, two additional input parameters have to be supplied: the relative abundance of young objects over the total, and the ratio of the scale height of young objects over the scale height of the total population.

The computation proceeds as described above, except that, when the contribution of young sources is computed, the density and scale height are scaled down by the specified factors. If the contribution of old sources is computed, the density is scaled properly, but the scale height is left unaffected.

4. Applications

Some examples of results obtained with the model are presented here. Figure 3 shows the variation of the expected log N($>S$)-log S curves with galactic latitude for two different stellar classes.

Figures 4 and 5 show the expected distributions in magnitude, color and f_X/f_V for stellar sources in a typical *Einstein* observation toward the galactic pole. The first set of plots shows the distributions for the whole stellar sample, while the second set shows the individual contributions for selected spectral classes.

We have used the model presented here to analyze the composition of the stellar component of the *Einstein* Extended Medium Sensitivity Survey (Gioia et al., 1990, EMSS), by matching the observed stellar source counts and distributions in $B-V$, m_V and f_X/f_V against the expected source counts. Preliminary results are described in a separate work (Favata et al., 1991), while a more detailed discussion is the object of forthcoming papers.

We have used this model to estimate the number of serendipitous stellar sources in deep observations (Sciortino et al., 1989; Vaiana, 1990) and plan to present in a future work a detailed prediction of the stellar component in the *ROSAT* and *AXAF* observations (Sciortino et al., 1991). We also use the model to

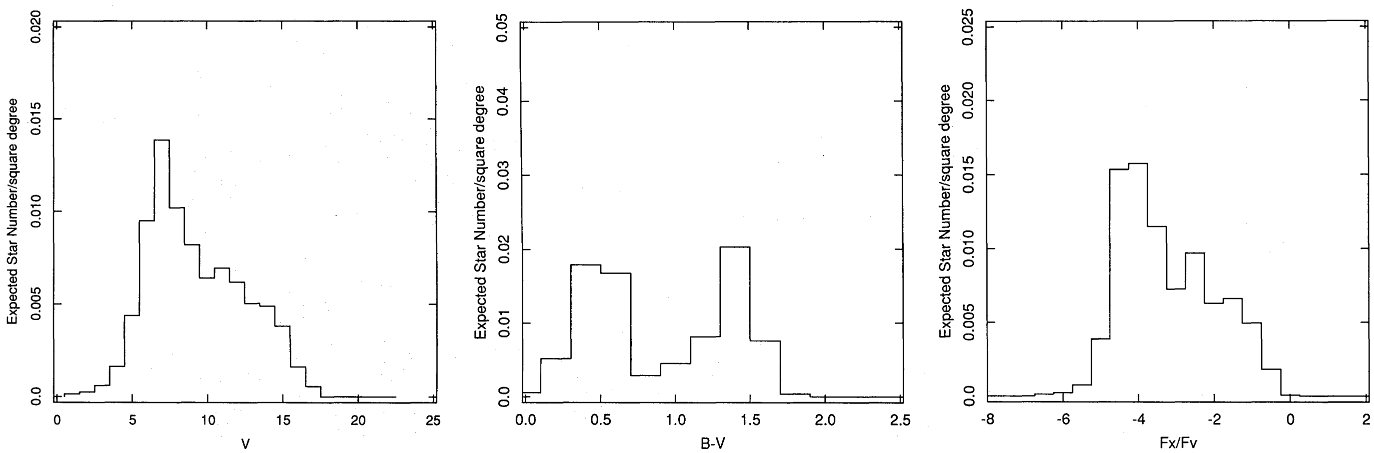

Fig. 4 The expected distributions in apparent magnitude (a)[left], $B - V$ color (b)[middle] and f_X/f_V (c)[right] for stellar sources observed in a typical *Einstein* IPC observation (limiting sensitivity 3×10^{-13}erg cm^{-2}sec^{-1}) toward the galactic pole. All dwarf stars with $B - V > 0$ have been added up in these figures. For all computation a coronal temperature of main sequence stars of 0.3 keV has been assumed. Note that for this calculation M stars (with B-V > 1.44) have been subdivided into four groups, i.e fainter and brighter than $M_V = 13.8$, each with young and old subgroups, with distinct X-ray luminosity functions. The data shown are the total numbers for the four subgroups

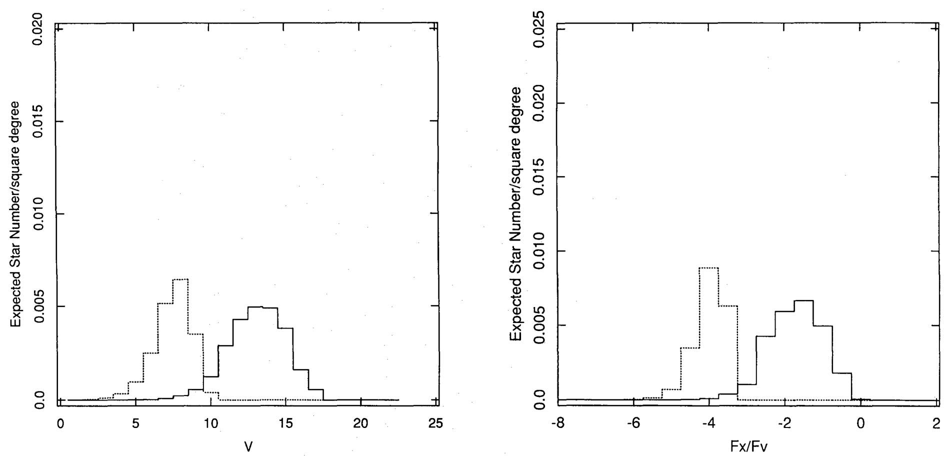

Fig. 5 The expected distributions in apparent magnitude (a) [left panel], and f_X/f_V (b) [right panel] for main sequence stars in the $0.5 < B - V < 0.8$ range (late F and G, dashed line) and $0.5 < B - V <$ M (M, continuous line) observed in a typical *Einstein* IPC observation (limiting sensitivity 3×10^{-13}erg cm^{-2}sec^{-1}) toward the galactic pole. For M stars the calculation has been performed in the same way as for previous figure.

perform exploratory computations to estimate the contribution of the different stellar types to the X-ray background (Micela, 1991) while a detailed account of these computations will be the argument of a fortcoming paper (Micela et al., 1991).

Planned applications include analyses of the stellar component of the forthcoming *ROSAT* survey and of the almost completed *EXOSAT* survey of coronal sources. Also, for future X-ray missions, our model can be used to compute the expected source density down to faint limiting fluxes and to estimate the stellar component to the source confusion limit for very deep X-ray observations.

Several improvements to the current version of the model are already planned. Those include a more detailed treatment of age related effects in the way outlined by Robin & Crézé (Robin & Crézé, 1986) and the proper treatment of the spheroidal component of the Galaxy, which might become important at very weak fluxes.

5. Conclusions

We have presented a model for the computation of expected stellar coronal source counts in the soft X-rays which proves to be a powerful tool for the analysis of the stellar content of unbiased X-ray surveys. In conjunction with such surveys it provides a new perspective on the global characteristics of stellar X-ray emission.

The model has proved to be a powerful tool in our research on the characteristic of stellar X-ray emission; we are currently using it and planning to enhance it with additional features. Given its flexibility, the model can and has been adapted to provide answer to different kind of questions, such as the expected log N($> S$)-log S relationship for stellar sources, the contribution of stellar sources to the soft X-ray background, and the expected stellar content of X-ray observation to be performed with future X-ray missions. The X-ray stellar counts, given the stronger dependence of X-ray luminosity on stellar age than "classical" optical indicators, can be used as a powerful diagnostic for model of stellar population distribution in the Galaxy.

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