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The large-scale distribution of X-ray active stars*

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Abstract. We analyse the large-scale sky distribution of 8593 X-ray emitting stars from the cross-correlation of the ROSAT All-Sky Survey sources with the Tycho catalog. We detect a density gradient from the galactic plane to the galactic pole which is attributed to the scale height of the young late type star population of the galactic disc. The data also show a low galactic latitude enhanced feature with respect to mean plane density. We fit the observed X-ray stellar surface density with a model consisting of a constant background component plus an exponential disc and derive for the best fit an inclination $i = 27.5^\circ \pm 1^\circ$ and an ascending node $l_\Omega = 282^\circ \pm 3^\circ$ with respect to the galactic plane. We discuss the Gould belt as a possible explanation to account for the observed enhancement.

Key words: X-ray: stars – Galaxy: stellar content – stars: late-type

1. Introduction

One of the major findings of stellar X-ray astronomy is the discovery of so-called "active stars", i.e., stars whose X-ray luminosity exceeds that of the Sun by many orders of magnitude. The first stellar soft X-ray surveys carried out with the *Einstein Observatory* (Vaiana et al. 1981, Fleming et al. 1989) showed that a small fraction of the stellar population is characterized by X-ray luminosities three (or more) orders of magnitude larger than the Sun at solar maximum. The stars producing these enormous X-ray outputs are in general of low mass ($< 2\,M_\odot$), rapidly rotating and usually young with characteristic ages of $\sim 10^7$ yrs (although the precise age of these stars is subject of some debate). Because of their large X-ray luminosities such stars can be detected at substantial distances. Given the typical limiting flux of the ROSAT All-Sky Survey (RASS, Voges 1997) of $\sim 2 \times 10^{-13}$ erg cm^{-2} sec^{-1}, the Sun can be detected out to a distance of only ~ 10 pc (Schmitt 1997). Stars with $10^3 \times L_{X,\odot}$ can then be detected out to a distance of ~ 300 pc, and hence the study of the large scale distribution of these sources becomes possible with the data provided by the RASS. Systematic identifications of all RASS sources detected down to the completeness limit of the RASS (≈ 0.03 cts s^{-1}) in sufficiently large test regions demonstrated a substantial contribution of the stellar population in such soft X-ray surveys. Depending on galactic latitude, active stars account for $\sim 30\%$ of the total X-ray source content at high galactic latitudes (Zickgraf et al. 1997) and up to $\sim 85\%$ at low galactic latitudes (Motch et al. 1997). The RASS is thus an efficient tool to select large samples of active (and hence presumably) young stars.

Unfortunately, the X-ray data by themselves do not permit a clear and unambiguous identification of an X-ray source with an astrophysical object class such as a star, a cataclysmic variable, an AGN etc.. The most reliable identifications of X-ray sources require optical follow-up observations of the objects found in and near the X-ray error boxes. Such an approach is rather time consuming and thus practically restricted to areas typically smaller than a few hundred deg^2 for the purpose of statistical studies (Motch et al. 1997, Zickgraf et al. 1997) or to identify objects of interest like T-Tauri candidates in star forming regions (Neuhäuser 1997 and references therein). It is - at least at present - not feasible to optically follow-up and identify all the RASS X-ray sources; this is, however, precisely what we need in order to study the large-scale distribution of active stars.

In order to tackle the problem, we decided to cross-correlate stellar catalogs with the RASS X-ray source list in order to construct samples of objects with known X-ray and optical properties. The major disadvantage of such an approach is that any bias present in the input catalog is propagated into the constructed subsample. In order to minimize bias, we chose to cross-correlate the RASS sources list with the Tycho catalog (ESA 1997). We emphasize that the cross-correlation of these two catalogs resulted in the largest sample of stellar X-ray sources with accurate position, magnitude, colors and proper motions constructed so far. This complete all-sky sample (hereafter referred as the *RASS - Tycho* sample) allows us to study the large-scale distribution of X-ray active stars in the solar neighbourhood.

2. The RASS - Tycho sample

The basic sample for our study consists of those objects obtained by cross-correlating the RASS X-ray source list ($\sim 150\,000$ at

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* Based on observations made with the ESA Hipparcos astrometry satellite

a likelihood threshold of 7) and the Tycho catalog (Hoeg et al. 1997), which contains astrometric (coordinates, trigonometric parallax, proper motion) and photometric (B_T, V_T, $(B - V)_T$) data of the brightest one million stars over the whole celestial sphere. The Tycho catalog is complete down to a magnitude limit of 10.5 but also contains fainter stars. All RASS sources were first searched for Tycho entries within a matching distance of 2 arcmin around the X-ray source position. Next the distribution of offsets between optical and X-ray position was examined. Specifically we found the number density (per unit sky area) of stars in a given offset interval to first increase and then decrease down to a nearly constant level, suggesting the obvious interpretation of the peak as those objects which are to be physically matched in both catalogs, while the constant background is ascribed to spurious identifications. In order to limit the contamination from this spurious population to a low level we restricted the maximally acceptable matching distance between optical and X-ray positions to 30 arcseconds, and found 13 875 matches out of which about 6% are expected to be spurious. Since we are concerned with statistical studies, a contamination of 6% ought not to affect any of the conclusions drawn in this paper. More details on the *RASS - Tycho* sample are given by Guillout et al. (1998).

Since both the RASS and Tycho catalogs are flux-limited, our *RASS - Tycho* sample is affected by the same two sources of bias. Unlike the Tycho catalog whose sensitivity is position independent, the RASS detection thresholds vary significantly over the sky. Guillout et al. (1998) show that regions with exposure times smaller than 204 sec have limiting sensitivities above 0.03 cts s^{-1}, but they amount to a small fraction of the whole sky. Thus we adopted $S = 0.03$ cts s^{-1} as our PSPC count-rate threshold, thereby reducing the total number of stars to 8 593, but avoiding the most serious bias for our analysis.

The magnitude limit of the Tycho catalog introduces a bias against dwarf stars of spectral type K and M. Such late type stars were not detected in the Tycho survey when located at distances greater than $\sim$ 20 to 60 pc. Yet from systematic X-ray surveys of such stars in the solar neighbourhood (Schmitt et al. 1995) we know that X-ray emission from such stars is very common, with X-ray luminosities easily reaching those typically observed for dwarf stars of spectral type G and F. Clearly, X-ray emitting dwarf stars of spectral type K and M are thus under-sampled in the *RASS - Tycho* sample with respect to earlier X-ray emitting stars (F,G). This bias should not affect our investigation because it is position independent.

3. The large-scale distribution of X-ray active stars

3.1. Gradient of star density towards the Galactic Pole

In Fig. 3 (see color plate) we show the surface density (in galactic coordinates) of the 8 593 *RASS - Tycho* stars using a count rate threshold $S_{th} = 0.03$ cts s^{-1}(see caption text for details). Fig. 3 clearly demonstrates a gradual decrease in stellar surface density from low to high galactic latitude; at the galactic poles the density of matched sources has decreased by 30% with respect to the plane. This decrease of stellar density is particularly noticeable above $|b| \sim 30°$. This global behavior confirms previous statistical studies based on smaller test areas.

Models describing the sky distribution of X-ray active stars (Micela et al. 1993, Guillout et al. 1996) predict that high-luminosity late-type (F - M) stars contribute a significant fraction to the stellar population detected in the RASS. Because of the small scale height of such stars, these models predict a strong gradient in stellar density from the galactic plane to the galactic pole in agreement with our qualitative observations. A quantitative comparison of the data with model predictions is the subject of a separate investigation (Guillout et al. 1998).

3.2. Analysis of the asymmetry

Closer inspection of the all-sky distribution of *Tycho* matched RASS sources shows a noticable asymmetry with respect to the galactic plane. Fig. 3 displays a broad enhanced density feature displaced from the galactic equator which shows up most prominently towards the third and fourth quadrants. The obvious question arises whether these enhancements are the result of individual spatially confined regions with an excess of X-ray emitting stars such as young open galactic clusters and star forming regions (SFR) or whether they are the result of a coherent large-scale structure. Young open clusters such as Pleiades, Hyades, etc as well as the Taurus-Auriga, Orion and Chameleon SFRs (see black circles Fig. 3) are clearly detectable stellar surface density enhancements in Fig. 3. Also, the spatially more extended SFRs like Scorpius, Centaurus, Lupus and Ophiuchus certainly do contribute to the enhancement in these sky regions, but it appears unlikely that they account for the whole feature extending over more than 180° of galactic longitude.

Interpreting then the observed density enhancement as a coherent feature, we proceeded to fit the observed X-ray stellar surface density with a simple model $B + A\,exp(-|l|/\lambda)$ consisting of a background component with constant strength B plus an exponential disc described by an amplitude A and scale height λ. The orientation of this disc model was allowed to vary and is hence described by an inclination angle i and an ascending node l_Ω with respect to galactic plane. For each choice of i and l_Ω the stellar surface density was longitudinally averaged over 360° in 5° wide latitude intervals leading to a total number of 36 latitude bins. The resulting one-dimensional distribution was then fitted with our exponential disc model and best fit values (in a χ^2 sense) of B, A and λ were computed. i and l_Ω were varied from 0° to 40° (0.5° step) and from 0° to 360° (1° step) respectively. In Fig. 1 we plot the variation of χ^2 with inclination and ascending node. The minimal χ^2 is located far away from the galactic equator at $i = 27.5°$ and $l_\Omega = 282°$. The 90% confidence limit for the joint distribution of i and l_Ω is defined by the $\chi^2 = \chi^2_{min} + 4.61$ contour and results in about 1° and 3° uncertainties on i and l_Ω respectively.

How significant is the introduction of an exponential disc and its being different from the plane of the Galaxy ? Let us define a model M1 “uniform background only” with one parameter (B), a model M2 “uniform background plus exponential

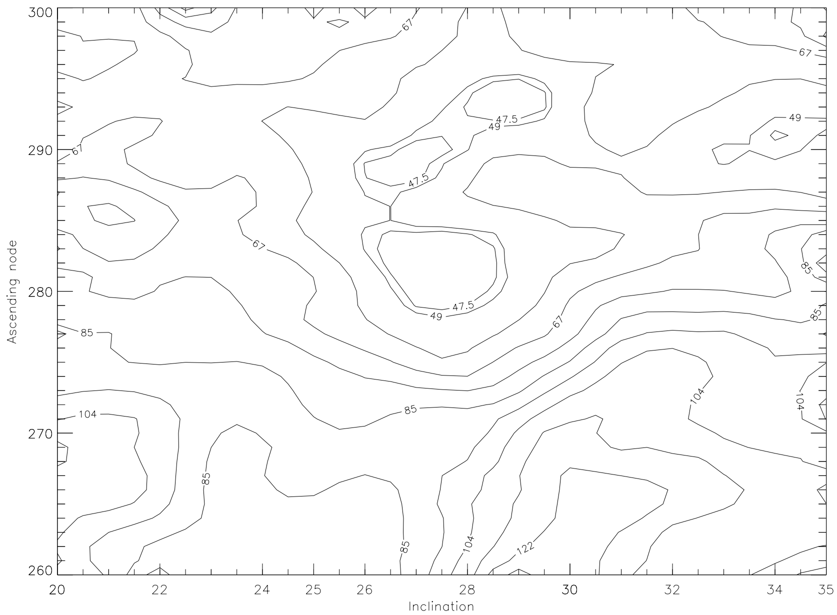

Fig. 1. χ^2 map isocontours resulting from an "Uniform background + exponential disc" fit to the observed surface star density in a reference system with inclination i and ascending node l_Ω with respect to galactic coordinates.

disc fixed at the galactic plane" with 3 parameters (B, A and λ), and a model M3 "uniform background plus exponential disc with free position" with 5 parameters (B, A, λ, i and l_Ω). The χ^2 test statistic for the best fit model M3 is $\chi^2_{min} = 42.89$ for 31 degrees of freedom (dof). Alternatively, the best fit model M2 has $\chi^2_{min} = 88.35$ for 33 dof and, finally, the best fit model M1, has $\chi^2_{min} = 185.46$ for 35 dof. Obviously, the models M1 and M2 are statistically not acceptable, but we note that the introduction of an exponential disc improves the fit considerably. Letting the disc's position float, does again improve the fit significantly. Following the procedure discussed by Eadie et al. (1971), we compute F = ((88.35-42.89)/42.89))*(36-5) = 32.86, but rejection of the additional two parameters at the 95% level would require F $<$ 4.16 which is obviously not the case. Thus we are justified in introducing the model M3; its minimal $\chi^2_{red} = 1.38$ also provides an acceptable fit in a statistical sense. This is demonstrated in Fig. 2, where we plot the longitudinally averaged star counts vs. latitude for the best fit model M3. We thus conclude that the introduction of an exponential disc tilted with respect to the Galactic plane leads to a good description of the spatial distribution of the stellar X-ray number counts.

3.3. Is the exponential disc Gould's Belt ?

More than one century ago astronomers noticed an asymmetry in the apparent distribution of the brightest stars on the sky with respect to galactic equator. The first detailed study of this distribution led B. Gould (1879) to the conclusion that these bright stars were distributed along a great circle crossing the Milky Way at an angle close to 20°, and subsequently this structure has become known under the name "Gould belt" (GB). Although numerous studies dealing with the distribution of bright stars, OB associations and young galactic clusters are consistent with GB, its existence as a physical entity is controversial, some authors claiming that it could be due to a coincidental superposition of a small number of young clusters, OB associations and SFRs, which are, however, physically unrelated. An extensive review of the GB system and its relation to the interstellar medium has been presented by Pöppel (1997), who also provides references to the relevant previous studies. The present-day picture of GB consists of a stellar component (population I stars with characteristic ages in the range 0 - 8 $\times$ 10^7 yrs, OB associations and young star clusters) located in a ring and associated interstellar matter. Somewhat different values of i ($\sim 18°$ to $23°$) and l_Ω ($\sim 275°$ to $290°$) are found depending on whether AOB-stars, dark clouds, open clusters, reflection nebulae are used to trace to the GB system. At any rate, it is clear that the inclination and ascending node of our exponential disc, i.e., $i = 27.5° \pm 1°$ and $l_\Omega = 282° \pm 3°$ are extremely close to the literature values and in fact consistent with them. We emphasize here that our values have been derived completely independently without any *a priori* knowledge of GB. Should we now interpret this close numerical coincidence simply as a conspiracy of Nature or are we to identify our exponential disc with GB ?

So far GB was recognized as an ensemble of OB associations, young galactic clusters and star forming regions but not as a population of mostly F - G "field" stars which we pick up preferentially in our *RASS - Tycho* sample. If one accepts the GB as a site of large scale star formation in the Galaxy (as evidenced by the young more massive stars tracing out the belt), there is no reason to assume that no low-mass stars are formed in this process. And indeed, Wichmann et al. (1997) identified an enhanced fraction of lithium-rich stars at b $\sim 18°$ adjacent to the Lupus SFR which they interpret as young low-mass members of the GB in this particular region.

Gas dynamic models of the neutral HI gas associated with the GB system (cf., Pöppel 1997 for an overview) assume a ring-like structure expanding in a field of differential (galactic) rotation with star formation taking place at the ring's outskirts. The ring's present major and minor semiaxes are $\sim$500 pc and

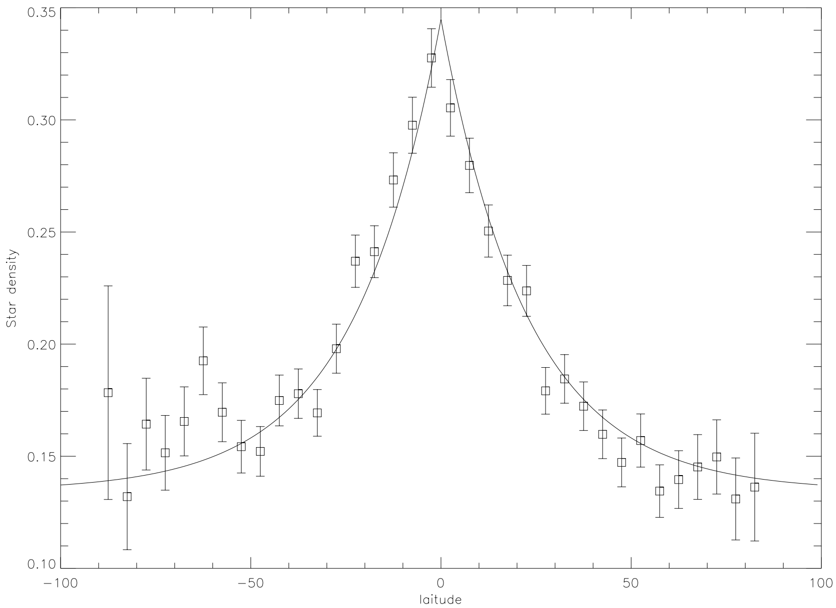

Fig. 2. Longitudinally averaged stellar surface density vs. latitude for the best fit model computed with $i = 27.5°$ and $l_\Omega = 282°$.

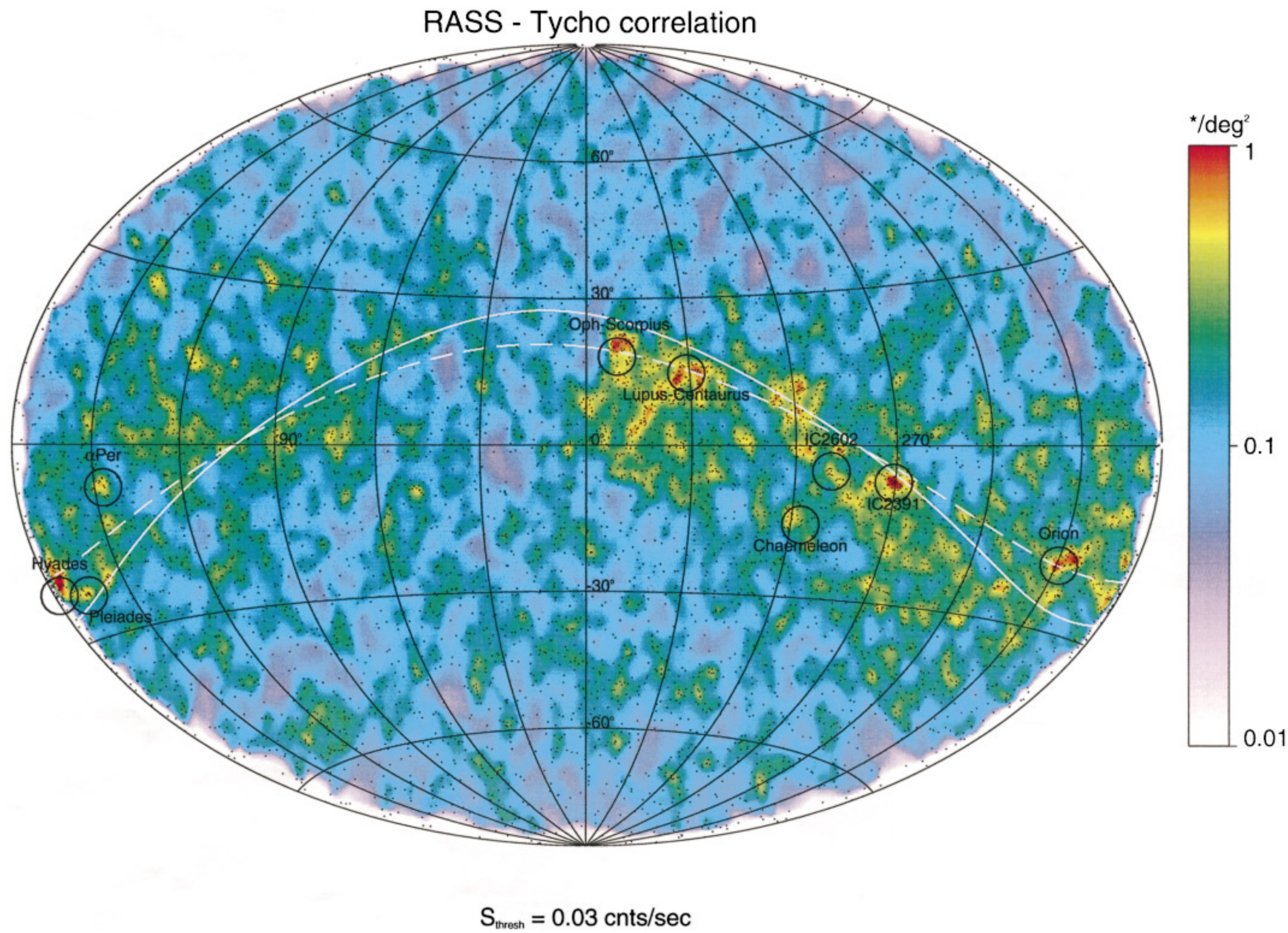

Fig. 3. All sky distribution in galactic coordinates (Aitoff projection) of 8593 *RASS - Tycho* stars at a PSPC count-rate threshold $S = 0.03$ cts s^{-1}. Each black dot is a match. Color codes the surface density on a logarithmic scale from 0.01 to 1 star/deg^2. The density enhancement at low galactic latitude is clearly visible. Note the asymmetry with respect to the galactic equator. Our best fit to the density distribution using an exponential disc model is indicated by the white full line while the dashed line indicates Gould belt. Black circles indicate young galactic clusters and star forming regions that show up in the *RASS - Tycho* sample at this PSPC threshold.

~ 300 pc respectively, the center of the ring and the expansion is located in or near the Cas-Tau association, with the Sun being about 140 pc off center. Given the range of X-ray luminosities observed for active late type stars ($L_X = 10^{27-31}$ erg s^{-1}) the stellar X-ray horizon at the completeness level of the RASS reaches out at most to 300 pc. Because of its geometry, the closest parts of the GB are within 150 pc of the Sun, in range of the *RASS - Tycho* sampling distance. This geometry could thus explain the largest surface densities observed in the third and fourth quadrants, where the ring comes closest to the Sun, while the smallest densities are observed in the first and second quadrants where the ring attains its maximum distance from the Sun.

Estimating photometric distances from the Tycho colors (Guillout et al. 1998) one finds characteristic distances of d $\sim$ 50 - 300 pc for the stars in the regions of enhanced surface density. Such a structure of slightly distant F - G main sequence stars with V $\geq$ 10 remains unnoticed at optical wavelengths due to lack of contrast especially in crowded fields at low galactic latitudes. At X-ray wavelengths the situation is completely different. Because of the sharp decrease of X-ray activity with age, stellar samples selected from X-ray surveys are greatly biased towards young stellar populations. Since the GB system is believed to comprise objects with ages $\leq$ 60 - 80 Myrs, it is thus quite natural that X-ray surveys should pick up low mass member stars of the GB system if they exist. Therefore the Gould belt appears to be a possible explanation to account for the density enhancement observed at low galactic latitude in our *RASS - Tycho* sample.

4. Conclusions and perspectives

We have analyzed the large scale distribution of about 8 600 stellar X-ray sources from the cross-correlation of the RASS with the Tycho catalogue. A surface density gradient between low and high galactic latitude regions expected from X-ray galactic models clearly appears in our data. In addition a broad overdensity shows up at low galactic latitude most prominently towards the third and fourth galactic quadrants. The observed surface density can be – empirically – best described by a model assuming a uniform background and an exponential disc. This disc is tilted with respect to the galactic plane with an inclination and ascending node very close to those of the GB system. We then propose to identify the observed density enhancement with the GB system. If an expanding ring is responsible for the formation of the GB, it should have triggered star formation in a large scale propagating process. The low mass stars accounting for the observed surface density excess could be the remaining debris of this process, still shining brightly in X-rays. A more detailed study of their characteristics such as distribution in distances, X-ray luminosity, proper motion is clearly needed to draw unambiguous conclusions. If our hypothesis can be confirmed it will provide new evidence in favour of interpreting the GB as a physical entity and for the occurrence of large-scale triggered star formation in the Galaxy.

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