X-RAY EMITTING PMS STARS IN UPPER SCO-CEN: THE X-RAY FAINT POPULATION

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ABSTRACT. We have performed an X-ray-based survey of the upper Sco-Cen star forming region, combining a deep ROSAT HRI pointing performed explicitly for this purpose with shallower ROSAT PSPC and HRI pointings from the public archive. Tens of X-ray sources are detected, down to limiting X-ray luminosities approximately one order of magnitude fainter that previously reported (on the basis of *Einstein* IPC data) for weak-line T-Tauri stars (WTTS) in the region. Additionally, the $\log N - \log S$ diagram for the detected source population shows no evidence for flattening, implying that, even at these much fainter limiting X-ray luminosities, the source population may still be severely undersampled. While optical observations which will lead to complete identification of the counterparts to the X-ray sources are under way, the available limited optical and X-ray evidence points toward most of them being PMS stars. The implications of the presence of a large population of relatively X-ray faint PMS sources in star-forming regions is discussed.

1. Introduction

The advent of imaging X-ray astronomy has brought a major change in the study of the low-mass population of star-forming regions (SFRs). Previously, low-mass pre-main-sequence (PMS) stars were identified in the form of the "classical T Tauri stars" (CTTS, from the prototype of the class), which show several peculiarities (emission lines, strong veiling, UV and IR excess) in their optical spectra, currently attributed to the presence of an accretion disk. *Einstein* IPC observations of nearby SFRs have shown that an additional population of low-mass PMS stars is present, with ages overlapping with the CTTS population, but which (presumably because of the lack of an accretion disk) show none of the spectral peculiarities which characterize CTTSs. Such optically quiet pre-main sequence stars have been named "weak-line T Tauri stars" (WTTS), as the only characteristic feature in their optical spectrum is the deep Li I line, caused by a still almost undepleted photospheric lithium abundance. Yet, thanks to their very high level of coronal activity (the more active stars showing X-ray luminosities in excess of $10^{31}\,\mathrm{erg\,s^{-1}}$), they are easily detected in X-ray surveys. In some SFRs X-ray selected WTTS's have been shown to be as numerous, or more numerous, than CTTSs, and thus a census of their population is an essential part to the study of a SFR.

The Scorpius-Centaurus OB association is rather nearby (at a distance of some 160 pc) and its well studied early-type members have an estimated age of $\simeq 4$ to $\simeq 10$ Myr. Yet, also because of its large projected size in the sky, very little was known until recently about its low-mass members. The first sizable population of low-mass PMS stars in Sco-Cen was identified by Walter et al. (1994 – W94) using *Einstein* IPC observations with a maximum limiting sensitivity (for stars at the distance of the Sco-Cen association) of $\simeq 10^{29.5}\,\mathrm{erg\,s^{-1}}$, at most. Their work, which surveyed about 7 square degrees in the so-called "upper Sco-Cen association" showed that a sizable low-mass PMS population is present in the region, and identified 28 of them with WTTS's mostly of G-K spectral types. More recent X-ray surveys, based on the ROSAT All-Sky Survey (RASS) data, studied much larger areas of the sky, and have identified several ($\simeq 100$) more new low-mass WTTS in the region (Preibisch et al. 1997). The RASS data have a similar limited sensitivity as the older *Einstein* data, and thus are detecting essentially the same population that was sampled by *Einstein*, although obviously yielding a much larger sample.

A key issue however is the completeness of the detected WTTS population. Are the above mentioned flux limiting surveys detecting the totality (or even the majority) of the low-mass PMS population in Sco-Cen? Or are they rather just picking up the X-ray-luminous tail of a much larger population with a broad distribution of X-ray luminosity? If (as postulated by W94) there is a mass-dependence of the X-ray luminosity, does this completeness fraction vary as a function of mass? Understanding the completeness of the sample is essential to be able to derive, for example, the intrinsic Initial Mass Function (IMF) in the region.

For this purpose, we have performed an X-ray survey of a small region in Sco-Cen, but with a much deeper limiting X-ray flux. Comparison with the *Einstein*- and RASS-detected population from the same area allows us to estimate the completeness of these larger-area surveys and thus eventually correct the IMFs derived from them.

2. The Sco-Cen Deep X-Ray Survey

For our survey we have obtained a deep (30 ks) ROSAT HRI observation (P.I. F. Favata), originally conceived as a follow-up study to the *Einstein* IPC observation I-5997. To this we have later added, from the public archive, a ROSAT PSPC 5.2 ks observation (P.I. F. Walter) of an area overlapping with our HRI frame, as well as a short (3.5 ks) ROSAT HRI field also partially overlapping with the PSPC field (P.I. M. Kunkel). We have also included two *Einstein* IPC fields (which were part of the W94 survey, but which were later re-processed, with a further 5 sources being found in them) overlapping with the ROSAT ones (I-5936 and I-5997) as well as the sources from the RASS Bright-Source Catalog for the surveyed area. The X-ray data analysis has been performed with a wavelet-based detection algorithm, and is discussed in detail by Sciortino et al. (1997), where a full account of this work is given, with a detailed source list. Here we'll discuss some global properties of the detected population.

Our X-ray survey detected a total of 50 distinct X-ray sources (with many of them being found in more than one X-ray observation), in an area of $\simeq 2$ square degrees of sky. In a similar area, the *Einstein*-based survey of W94 had detected 17 sources. The best limiting sensitivity of our survey is about one order of magnitude deeper than the *Einstein*- or RASS-based observations, so that we can detect Sco-Cen members with X-ray luminosities down to $\simeq 10^{28.5}\,\mathrm{erg\,s^{-1}}$. The $\log N$–$\log S$ of the detected source population is shown in Fig. 1, which compares the $\log N$–$\log S$ derived from our survey with the one derived from the *Einstein* data. As it can be seen, a substantial X-ray faint source population is present in the region, and there is no evidence for the $\log N$–$\log S$ to flatten at the fainter flux, making it likely that the actual X-ray source population in the region extends to fainter X-ray sources.

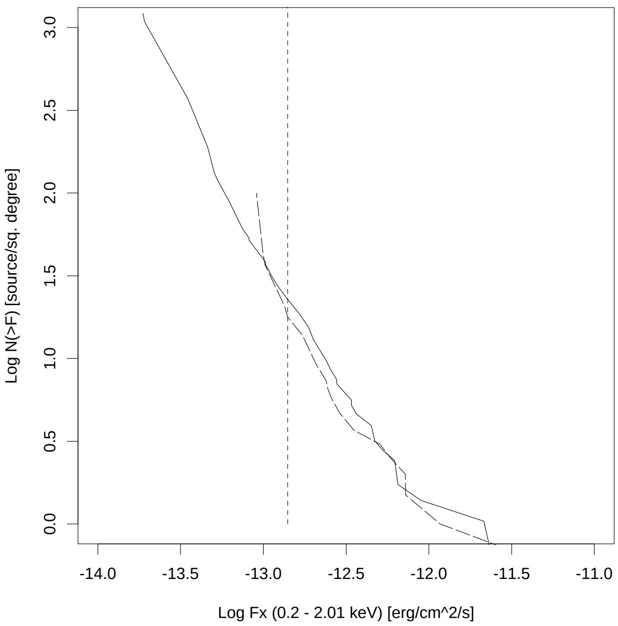

Fig. 1. The continuous line is the $\log N$–$\log S$ for the X-ray sources detected in our ROSAT-based deep X-ray survey of a $\simeq$ 2 square degrees in the Sco-Cen star-forming region, while the dashed line is the $\log N$–$\log S$ for the sources detected in the two *Einstein* IPC fields from the same region discussed in the text. The short-dashed vertical line represent the X-ray flux of the faintest source detected in the W94 survey.

We are currently in the process of identifying the optical counterparts of the X-ray sources detected in our survey. Photometric observations have been obtained, while the scheduled run of spectroscopic observations has been unfortunately lost to bad weather and will thus have to be rescheduled. We however had obtained some preliminary spectroscopic observations for some of the fainter IPC sources (the ones not in W94), showing that they indeed have, as optical counterpart, low-mass WTTS's. Additionally, the colors of most of the candidate optical counterparts to the X-ray sources are compatible with their being a low-mass star. The X-ray hardness ratio of most of the X-ray sources is compatible with their having thermal spectra with a moderate amount of interstellar absorption (compatible with the expected column density at the distance of Sco-Cen), and analysis of the spectra of the three X-ray brightest sources also shows that they are likely to be of coronal nature. The expected contamination of our survey from extragalactic sources is $\simeq$ 7 X-ray sources. while the contamination from disk-population Galactic stars (foreground objects) is estimated at another $\simeq$ 1 X-ray sources. We thus consider it highly plausible that the majority if not all of the remaining X-ray sources sources detected in our survey indeed are low-mass members of the Sco-Cen star-forming region.

3. Conclusions

The results of our survey show that the census of the WTTS population in Sco-Cen based on the relatively shallow *Einstein*- and RASS-based data are likely to be severely incomplete, with a much larger X-ray faint WTTS population looming in the background. A detailed assessment of the nature of this population will have to wait for the completion of the optical identification work. Given that our preliminary data are strongly indicative of their being PMS stars, there are (at least) three possible explanations: **a)** they (mostly) are stars with masses (and thus X-ray luminosities) smaller that the ones detected in the shallower surveys, **b)** they are X-ray fainter stars with masses and ages in the same range as the population studied by W94, or **c)** they are an older (and thus) X-ray-fainter population. Under hypothesis **a)** the IMF derived by W94 would need to be significantly revised at the low-mass end. Our photometry shows that some of the optical counterparts have magnitudes comparable with the stars of W94, and thus that they cannot all be lower-mass WTTS. Under hypothesis **b)** the normalization of the IMF would need to be scaled upwards in a significant way. Finally, if hypothesis **c)** were to be verified, the star-formation history of the Sco-Cen region would need to be revised considerably.

More in general, our survey has shown the importance of ensuring that one is sampling the complete X-ray luminosity function of a population under study and that completeness of shallow flux-limited surveys cannot be taken for granted. We plan to further extend our search for X-ray faint WTTS in the Sco-Cen region by performing deeper observations of the same region with the future generation of X-ray observatories, and in particular with XMM.

References

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