CAMBRIDGE JOURNALS

Proof Delivery Form

Proceedings of the International Astronomical Union

Date of delivery: 5 May 2016

Journal and vol/article ref: IAU 1600866

Number of pages (not including this page): 4

This proof is sent to you on behalf of Cambridge University Press. Please check the proofs carefully. Make any corrections necessary on a hardcopy and answer queries on each page of the proofs

Please return the **marked proof** within 5 days of receipt to:

Managing editor of this symposium

Authors are strongly advised to read these proofs thoroughly because any errors missed may appear in the final published paper. This will be your ONLY chance to correct your proof. Once published, either online or in print, no further changes can be made.

To avoid delay from overseas, please send the proof by airmail or courier.

If you have **no corrections** to make, please email **managing editor** to save having to return your paper proof. If corrections are light, you can also send them by email, quoting both page and line number.

- The proof is sent to you for correction of typographical errors only. Revision of the substance of the text is not permitted, unless discussed with the editor of the journal. Only **one** set of corrections are permitted.
- Please answer carefully any author queries.
- Corrections which do NOT follow journal style will not be accepted.
- A new copy of a figure must be provided if correction of anything other than a typographical error introduced by the typesetter is required.

If you do not send any corrections to the editor within 5 days, we will assume your proof is acceptable.

- If you have problems with the file please contact **lwebb@cambridge.org**

Please note that this pdf is for proof checking purposes only. It should not be distributed to third parties and may not represent the final published version.

Important: you must return any forms included with your proof. We cannot publish your article if you have not returned your signed copyright form.

NOTE - for further information about **Journals Production** please consult our **FAQs** at http://journals.cambridge.org/production_faqs

Author queries:

Typesetter queries:

Non-printed material:

Solar and Stellar Flares and their Effects on Planets
Proceedings IAU Symposium No. 320, 2015
A.G. Kosovichev, S.L. Hawley & P. Heinzel, eds.

doi:10.1017/S1743921316008668

The Frequency of stellar X-ray flares from a large-scale XMM-Newton sample

John P. Pye and Simon R. Rosen
University of Leicester, Dept. of Physics & Astronomy,
Leicester, LE1 7RH, U.K.
email: pye@le.ac.uk ; srr11@le.ac.uk

Abstract. We present estimates of cool-star X-ray flare rates determined from the XMM-Tycho survey (Pye *et al.* 2015, A&A, 581, A28), and compare them with previously published values for the Sun and for other stellar EUV and white-light samples. We demonstrate the importance of applying appropriate corrections, especially in regard to the total, effective size of the stellar sample. Our results are broadly consistent with rates reported in the literature for Kepler white-light flares from solar-type stars, and with extrapolations of solar flare rates, indicating the potential of stellar X-ray flare observations to address issues such as 'space weather' in exoplanetary systems and our own solar system.

Keywords. X-rays: stars - stars: flare - stars: activity - stars: coronae - surveys - catalogs

1. Introduction

The XMM-Newton Serendipitous Source Catalogue (Watson *et al.* 2009) has been used as the basis for a uniform, large-scale survey of X-ray flares from late-type (i.e. spectral type F–M) stars in the Hipparcos Tycho catalogue (Høg *et al.* 2000), as reported by Pye *et al.* (2015). The XMM catalogue and its associated data products provide an excellent basis for a comprehensive and sensitive survey of stellar flares – both from targeted active stars and from those observed serendipitously in the half-degree diameter field-of-view of each observation. Our sample contains ~ 130 flares with well-observed profiles; they originate from ~ 70 stars. The flares range in duration from $\sim 10^3$ to $\sim 10^4$ s, have peak X-ray fluxes from $\sim 10^{-13}$ to $\sim 10^{-11}$ erg cm^{-2} s^{-1}, peak X-ray luminosities from $\sim 10^{29}$ to $\sim 10^{32}$ erg s^{-1}, and X-ray energy output from $\sim 10^{32}$ to $\sim 10^{35}$ erg. Most of the 36 flaring, serendipitously-observed stars have little previously reported information, though $\sim 70\%$ of them have assigned spectral types (mostly F–K, with a few M). The total number of serendipitously-observed Tycho stars with 2XMM light-curves (i.e. ones for which we could potentially detect flaring) was ~ 500.

In this paper, we focus on and extend one specific aspect of the work reported by Pye *et al.* (2015), namely the rate of flaring as derived from the serendipitous sample, and comparison with other stellar and solar results reported in the literature.

2. Flare rates and frequency distributions

The serendipitous observations provide an unbiased (with respect to stellar activity) study of flare energetics. The serendipitous sample demonstrates the need for care when calculating flaring rates, especially when normalising the number of flares to a total exposure time, where it is important to consider both the stars seen to flare and those measured as non-variable, since in our survey, the latter outnumber the former by more than a factor ten. Both sets of stars appear very similar in terms of the distributions of

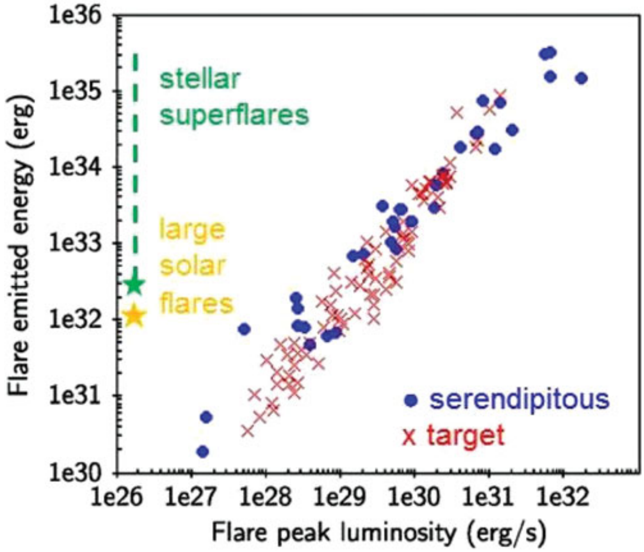

Figure 1. Total X-ray emitted energy E_X versus flare peak X-ray luminosity (energy band 0.2 – 12 keV) (after Pye *et al.* 2015). Only 'fully-observed' flares are shown (see Pye *et al.* 2015 for details). Key to symbols: blue circles: Serendipitously-observed stars; red diagonal crosses: Target stars. Nominal values of E_X for large solar flares (yellow star symbol) and stellar superflares (green star symbol and dashed line) are indicated.

general properties such as quiescent X-ray luminosity. It may well be that the lack of observed flaring arises simply from a combination of the relatively limited observation time for each star and the range of activity levels exhibited by cool stars in general (Pye *et al.* 2015).

2.1. *Comparison with solar and other stellar results*

Fig. 1 shows the total X-ray emitted energy (E_X) versus flare peak X-ray luminosity ($L_{X,peak}$), for our serendipitous and target samples, together with an indication of the regions occupied by large solar flares and stellar superflares (see e.g. Güdel 2004 ; Schrijver *et al.* 2012; Shibayama *et al.* 2013), showing that many of the XMM-Tycho flares come within the 'superflare' category, and that there is substantial overlap in terms of energetics between the observed stellar flares and large solar flares.

We have constructed frequency distributions for E_X and derived flare rates above specified thresholds (Pye *et al.* 2015). Due to the small numbers of stars, and the lack of detailed information for most of the serendipitous sample, we have not attempted to divide them into different categories; hence the distributions and statistics refer to a rather heterogeneous collection of stellar types. We also note that there are large uncertainties due to the relatively small number of flares observed, and there may be incompleteness effects, as discussed by Pye *et al.* (2015).

In Fig. 2, our results are compared with published values for solar flares and for other stellar surveys. The latter comprise EUV observations of several known, active stars (Audard *et al.* 2000), and white-light stellar flares from solar-type stars observed by the Kepler mission (e.g. Maehara *et al.* 2015). Note that Fig. 2 represents bolometric energy (E_{bol}); we have converted our X-ray values using $E_{bol}/E_X = 4$, i.e. within the range $E_{bol}/E_X \sim 3$–5 suggested by Schrijver *et al.* (2012).

We summarise our findings and comparisons as follows.

- Previously reported (e.g. Schrijver *et al.* 2012) comparisons of solar-flare frequency

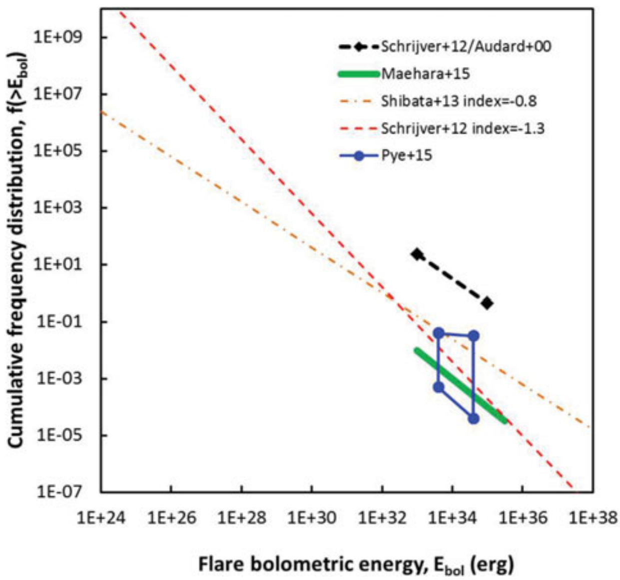

Figure 2. Comparison of various solar- and stellar-flare cumulative frequency distributions, $f(> E_{\rm bol})$ (number per year per star) in terms of bolometric energy, $E_{\rm bol}$ (erg). Key to symbols: blue solid lines forming a trapezium, with circle symbols: X-ray (this work; Pye *et al.* 2015), lower pair of points are scaled according to stellar coronal quiescent luminosity, upper pair are not scaled; thick green solid line: Kepler white-light results (Maehara *et al.* 2015); thick black dashed line with diamond symbols: EUV results scaled according to stellar coronal quiescent luminosity (after Audard *et al.* 2000; Schrijver *et al.* 2012); red dashed line: power-law with index -1.3, representing solar results and extrapolation to high energies (Schrijver *et al.* 2012); orange dash-dot line: power-law with index -0.8, representing solar results and extrapolation to high energies (Shibata *et al.* 2013).

distributions (albeit somewhat extrapolated) with scaled (downwards) EUV distributions for several highly-active stars (from Audard *et al.* 2000) have suggested that the Sun appears to lie significantly below other stars, by a factor ~ 100, even after allowing for the differences in overall, 'quiescent' coronal (EUV/X-ray) luminosity. Our results (see also Shibayama *et al.* 2013) indicate that this is likely to be due to the bias from having only very active stars in the EUV sample.

- Our scaled XMM-Tycho flare rates (for $E_{\rm X} > 10^{33}$ erg) are:
  - a factor $\sim 2 \times 10^4$ lower than the highly-active-star EUV scaled rates;
  - broadly consistent with extrapolated solar rates (Schrijver *et al.* 2012; Shibayama *et al.* 2013);
  - broadly consistent with Kepler white-light rates (e.g. Shibayama *et al.* 2013; Maehara *et al.* 2015).

3. Future work

We summarise here several obvious areas in which this work may be carried forward. Our aim would be to have a survey with well-characterised stellar properties and of sufficient size to enable, for example, estimation of flare rates for solar-type stars (c.f. the visible-light results, see e.g. the review by Shibata, this volume).

- Detailed characterisation of the stars, via follow-up at optical wavelengths: spectroscopy to determine whether a star is single or comprises a close binary system, and to measure rotation velocity ($v \sin i$) and, where applicable, orbital period; photometry (typically over durations of ∼weeks to ∼months), to determine rotation period.

• Modelling the 3-dimensional spatial distribution of the stars, to enable better correction for incompleteness effects.

• Extension of the X-ray observations, by taking account of the factor ~ 3 increase in data now available from the 3XMM catalogue (Rosen *et al.* 2015) and utilising the time-variability data products and characterisation to be produced by the EU-FP7 EXTraS project (http://www.extras-fp7.eu/ ; De Luca *et al.* 2015; Pizzocaro *et al.* 2015).

• Extension of the stellar catalogues, especially to expand the coverage of dM-type stars.

In the long-term, wide-field X-ray surveys, e.g. with 'Lobster-eye' optics (e.g. Osborne *et al.* 2013), may be expected to yield many observations of stellar flares.

4. Conclusions

We have shown broad consistency between our X-ray flare rates and those extrapolated and scaled from the Sun and from stellar white-light observations. There are a number of possible future activities which would carry this work forward in terms of larger sample sizes and greater knowledge of the stellar properties, thus improving our insights into both the mechanisms for flare generation, and the 'space weather' effects of flares on the stellar-system environment and any exoplanets present.

References

Audard, M., Güdel, M., Drake, J. J., & Kashyap, V. L. 2000, *ApJ*, 541, 396

De Luca, A., Salvaterra, R., & Tiengo, A., *et al.* 2015, in: Longo, Napolitano, Marconi, Paolillo & Iodice (eds.), *The Universe of Digital Sky Surveys*, *to be published in Ap&SSP*, arXiv:1508.07146

Güdel, M. 2004, *A&AR*, 12, 71

Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, *A&A*, 355, L27

Maehara, H., Shibayama, T., & Notsu, Y., *et al.* 2015, *Earth, Planets & Space*, 67, 59

Osborne, J. P., O'Brien, P., Evans, P., *et al.* 2013, in: A. J. Castro-Tirado, J. Gorosabel, & I. H. Park (eds.), EAS Publications Series, Vol. 61, 625

Pizzocaro, D., Stelzer, B., & Paladini, A., *et al.* 2015, *submitted to A&A*

Pye, J. P., Rosen, S., Fyfe, D., & Schröder, A. C. 2015, *A&A*, 581, A28

Rosen, S. R., Webb, N. A., & Watson, M. G., *et al.* 2015, *submitted to A&A*, arXiv:1504.07051

Schrijver, C. J., Beer, J., Baltensperger, U., et al. 2012, *J. Geophys. Res. (Space Physics)*, 117, 8103

Shibata, K., Isobe, H., & Hillier, A., *et al.* 2013, *PASJ*, 65, 49

Shibayama, T., Maehara, H., & Notsu, S., *et al.* 2013, *ApJS*, 209, 5

Watson, M. G., Schröder, A. C., & Fyfe, D., *et al.* 2009, *A&A*, 493, 339