X-ray line coincidence photopumping in a solar flare

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There are many instances of line coincidence photopumping in astrophysics at optical and ultraviolet wavelengths, with the most famous example probably being Bowen fluorescence (pumping of O III 303.80 Å by He II), but none to our knowledge at X-rays. However, we have identified a scheme where a He-like line of Ne IX at 11.000 Å is photopumped by He-like Na X at 11.003 Å, which predicts significant intensity enhancement in the Ne IX 82.76 Å transition under physical conditions found in solar flare plasmas. A comparison of our theoretical models with published X-ray observations of a solar flare obtained during a rocket flight does indeed provide evidence for line enhancement, with the measured degree of enhancement being consistent with that expected from theory. Further detections of 82.76 Å line enhancement during flares on active, late-type stars would be important, because as well as being an interesting plasma effect, such measurements would in principle also provide a powerful new diagnostic for determining the sizes of flare loops in these distant, spatially-unresolved, astronomical sources.

Line coincidence photopumping — the radiative excitation of a transition in a species due to line emission in another species at a coincident wavelength — was first recognised in astrophysics by Bowen (1934). This process, termed Bowen fluorescence, results from the wavelength coincidence of the $2p^2\ ^3P_2$–$2p3d\ ^3P_2$ transition of O III at 303.80 Å with the He II $1s\ ^2S$–$2p\ ^2P$ resonance line, with the latter pumping the former, leading to O III emission features linked to the $2p3d\ ^3P_2$ level which are much stronger than would be expected in nebular plasmas. Since the seminal paper by Bowen, numerous examples of line coincidence photopumping in astrophysical plasmas have been identified, although the O III/He II case remains that at the shortest wavelength (see Table 11.1 of Hartman 2013). In particular, there has been no detection to our knowledge of photopumping at X-ray wavelengths in a high temperature (coronal) astrophysical source.

By contrast, there has been an enormous amount of research on X-ray line coincidence photopumping schemes in laboratory plasmas, due to the possibility of developing X-ray lasers via this technique. Although lasing has not been achieved, one experimental setup by Porter et al. (1992) involving the helium-like ions of sodium (Na X) and neon (Ne IX) did demonstrate population inversion. We have therefore chosen this scheme to model in astrophysical environments as it probably provides the best chance of success, and it is shown in Figure 1. The $1s^2\ ^1S$–$1s2p\ ^1P$ resonance line of Na X at 11.003 Å pumps the Ne IX $1s^2\ ^1S$–$1s4p\ ^1P$ transition at 11.000 Å. In laboratory plasmas, there is collisional redistribution from the $1s4p\ ^1P$ to other $1s4\ell$ (ℓ = s, d, f) levels due to the high electron density, but this does not happen in the lower density astrophysical case. Instead, electrons in $1s4p\ ^1P$ decay to $1s3s\ ^1S$ or $1s3d\ ^1D$, producing the emission lines at 224.34 and 233.52 Å, respectively. Subsequently, $1s3s\ ^1S$ and $1s3d\ ^1D$ both decay to $1s2p\ ^1P$, producing 82.76 and 81.58 Å, respectively.

We have used the GALAXY modeling code of Rose (1995) to calculate the expected enhancements in the above lines of Ne IX due to photopumping as a function of electron density, N_e, and plasma pathlength, L (see Methods). Our results for the 82.76 Å line are shown in Figure 2 for a range of N_e (= 10^{10}–10^{13} cm^{-3}) and L (= 10^9–10^{13} cm) appropriate to flaring coronal loops in the Sun and other active, late-type stars (Shibata and Magara 2011; Mullan et al. 2006). Predicted enhancements in the 224.34 and 233.52 Å lines are similar to those for

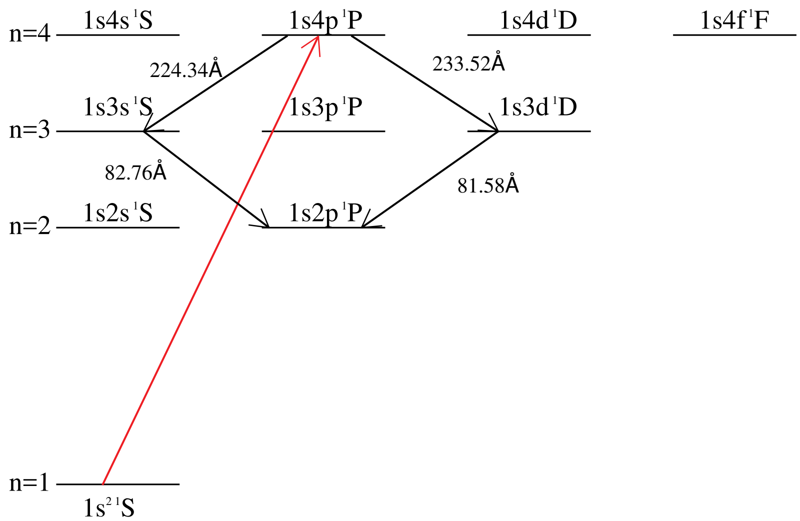

Figure 1: Energy level diagram for Ne IX showing the X-ray photopumping scheme. The $1s^2$ ^1S – $1s4p$ ^1P transition at 11.000 Å is photopumped by the $1s^2$ ^1S – $1s2p$ ^1P resonance line of Na X at 11.003 Å. Subsequently, the electrons in $1s4p$ ^1P decay to $1s3s$ ^1S or $1s3d$ ^1D, producing the 224.34 and 233.52 Å emission lines, respectively, which in turn both decay to $1s2p$ ^1P, producing 82.76 and 81.58 Å, respectively.

82.76 Å, while for 81.58 Å they are about a factor of 20 smaller. An inspection of Figure 2 reveals that the enhancement factor does not depend strongly on the electron density unless $N_e \geq 10^{11}$ cm^{-3}, but is sensitive to the pathlength for $L \geq 10^{10}$ cm.

In solar and late-type stellar flare spectra, the Ne IX 224.34 and 233.52 Å lines are unfortunately blended with the strong Fe XIV 224.35 Å and O IV 233.55 Å features, respectively. A synthetic flare spectrum calculated with the CHIANTI database (see Methods) indicates that Ne IX makes a contribution of $<1\%$ to the total line flux in both instances, while solar flare observations confirm that the features are due to Fe XIV and O IV (Bhatia et al. 1994; Widing 1982). In the case of the 81.38 Å transition, the predicted enhancement is too small even under optimal conditions to detect the feature.

However, the situation is different for the 1s2p ^{1}P – 1s3s ^{1}S transition at 82.76 Å. Although this lies in a relatively unexplored spectral region, one very interesting dataset is the soft X-ray rocket spectrum of a solar flare between 10–95 Å obtained by Acton et al. (1985) at high spectral resolution (0.02 Å). These authors note an unidentified emission line at 82.76 Å, which is listed as blended. The National Institute of Standards and Technology (NIST) database (at https://www.nist.gov/) lists the wavelength of the 1s2p ^{1}P - 1s3s ^{1}S transition as 82.76 Å. We have recalculated the wavelength of the transition (see Methods) and predict it to be 82.761 Å, confirming the original NIST value.

The CHIANTI synthetic flare spectrum indicates that, even in the absence of photopumping, the Ne IX 82.76 Å transition should dominate the emission feature observed by Action et al. (1985), contributing at least 50% to the total line flux. Furthermore, the Acton et al. spectrum also contains the Ne IX 1s^2 ^{1}S–1s2p ^{1}P resonance line at 13.45 Å and 1s^2 ^{1}S–1s2s ^{3}S forbidden line at 13.70 Å. The electron density of the flare is $N_e \sim 10^{11}$ cm^{-3} (Brown et al. 1986), for which CHIANTI predicts line intensity ratios (in photon units) of 82.76/13.45 = 0.019 and 82.76/13.70 = 0.020, compared to experimental values of 0.20 and 0.24, respectively. We note that the measured and theoretical CHIANTI 13.45/13.70 intensity ratios are both 1.2, indicating no blending in these features. Hence, assuming that Ne IX is responsible for $\sim 50\%$ of the 82.76 Å line intensity, both the 82.76/13.45 and 82.76/13.70 ratios indicate that

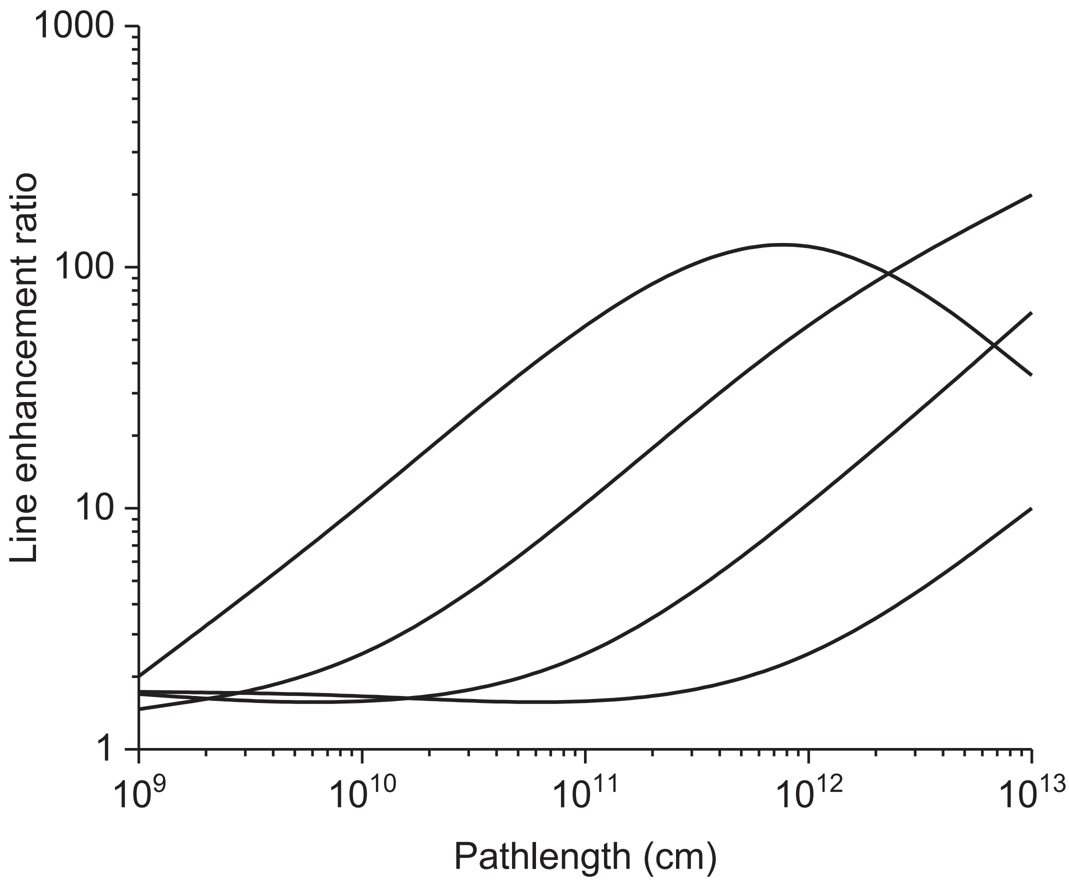

Figure 2: Plot of the enhancement factor (i.e. line intensity of the photopumped line divided by that when there is no pumping) for the 82.76 Å line of Ne IX, calculated with the GALAXY code as a function of pathlength L for values of electron density of (from bottom to top) $N_e = 10^{10}$, 10^{11}, 10^{12} and $10^{13}\,\mathrm{cm}^{-3}$. The adopted electron temperature is that of maximum Ne IX fractional adundance in ionization equilibrium, $T_e = 1.6\times10^6$ K (Bryans et al. 2009), although we note that the results are not very sensitive to T_e (see Methods). The decrease in enhancement at large L for the $N_e = 10^{13}\,\mathrm{cm}^{-3}$ curve is due to the onset of opacity in the 82.76 Å line.

82.76 Å is enhanced by a factor of ~ 5. The maximum flare loop length for the Sun is L $\sim 10^{10}$ cm (Shibata & Magara 2011), which from Figure 2 at $N_e = 10^{11}$ cm^{-3} would indicate an expected enhancement of a factor of ~ 2, which is not too different from the measured value.

A similar enhancement is found if we consider strong, isolated emission lines closer to 82.76 Å. For example, the measured line intensity ratios of 82.76 Å to Fe XV 73.47 Å and Fe XVI 76.80 Å are 82.76/73.47 = 0.52 and 82.76/76.80 = 1.9 from Acton et al. (1985), compared to theoretical values of 0.16 and 0.30, respectively, predicted by the CHIANTI flare spectrum. These in turn imply enhancements in 82.76 Å of factors of ~ 1.6 and ~ 3, respectively, once again in reasonable agreement with that expected from Figure 2.

Although the above solar flare results are very encouraging, providing to our knowledge the first evidence for X-ray line coincidence photopumping in an astrophysical source, they must be treated with some caution. The flare spectrum of Acton et al. (1985), recorded on photographic film, is no longer accessible and hence the quality of the 82.76 Å line measurement (and indeed those of other transitions) cannot be confirmed. In addition, the 13.45 + 13.70 Å and 82.76 Å features lie close to opposite ends of the flare wavelength coverage (10–95 Å), so that instrumental sensitivity calibration may be an issue.

Clearly, further observations of the Ne IX 82.76 Å line are desirable to completely confirm our findings, ideally for flare plasmas with larger values of electron density and pathlength than the solar case, as Figure 2 indicates these would show even greater enhancement factors. Such plasmas are provided by late-type stellar coronal sources, many of which are believed to have high N_e ($\geq 10^{11}$ cm^{-3}), large L ($\sim 10^{10} - 10^{12}$ cm) flaring loops (Mullan et al. 2006). Furthermore, spectroscopic instrumentation on the currently-operating Chandra astronomical satellite covers the relevant X-ray wavelength range to detect 82.76 Å (Brinkman et al. 2000), and hence there is the possibility of obtaining spectral data in the future to search for the line.

However, although the further detection of intensity enhancement in 82.76 Å due to x-ray line coincidence photopumping would be extremely interesting, it would probably not be the most important outcome of such observatiuons. The electron density of an emitting flare plasma is relatively straightforward to determine from Chandra spectra, due to the presence of numerous N_e-diagnostic emission lines (Mewe et al. 2001). By contrast, the methods developed for determining flare loop pathlengths L require various assumptions to be made. For example, that of Haisch (1983) assumes no additional flare heating during flare decay, while the method of Shibata & Yokoyama (2002) requires an assumption of the value for the magnetic field strength (see Mullan et al. 2006 for more details on these and other methods). A comparison of the 82.76 Å line enhancement factor and flare electron density measured from a Chandra spectrum with the results in Figure 2 will give an independent determination of L, and in particular will yield values for high L stellar coronal plasmas, as the enhancement factor is predicted to become very sensitive to L under such conditions. These measurements of L may be compared with those derived using other methods, to determine the reliability of the latter and the assumptions made. Indeed, in principle the enhancement effect could provide a very powerful diagnostic for determining plasma pathlengths in any remote, spatially-unresolved, astrophysical source which shows similar values of N_e and L to the late-type stellar cases, such as the coronal regions of active galactic nuclei (see, for example, Reeves et al. 2016).

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Addendum Acknowledgements FPK, KP and MM are grateful to the Science and Technology Facilities Council (UK) for financial support. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 606862 (F-CHROMA). CHIANTI is a collaborative project involving George Mason University, the University of Michigan (USA) and the

University of Cambridge (UK).

Competing Interests The authors declare they have no competing financial interests.

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Author Contribution Statement FPK, KP, MM and DJC created the synthetic flare spectrum using CHIANTI, and undertook the analysis of the solar flare data. They also developed the ideas for future work with the Chandra satellite, including the use of the line enhancement factor as a plasma diagnostic. SJR, JF and DH generated the line enhancement models with the GALAXY code. JN, WJ and KTC performed new calculations for the wavelength of the 82.76 Å line of Ne IX.

Data Availability Statement The results of the GALAXY models for the line enhancement are available from one of the authors, Steven Rose (s.rose@imperial.ac.uk), on request. The CHIANTI software packages are freely available from its website http://www.chiantidatabase.org/.

Methods

Calculations of line intensity enhancements with the GALAXY modelling code The model used for the calculations reported in this paper, called GALAXY, is described in detail in Rose (1995). Briefly, GALAXY is a time-independent collisional-radiative model that describes the excitation and ionisation within a plasma at a given electron and ion temperature and a given electron number density. It can simulate mixtures of elements through a self-consistent calculation of electron number density. All the atomic data, including energy levels, collisional and radiative excitation and ionisation rates, plus autoionisation and dielectronic recombination rates, are generated internally using simple screened-hydrogenic methods. The description of levels is in the *nl*-coupled average-of-configuration approximation. We consider a mixture of H, He, Ne and Na, with the solar coronal abundances of Schmelz et al. (2012). Using the *nl*-coupled configuration average description, GALAXY considers for Ne and Na the fully stripped ions as well as the H-like configurations 1s, 2s, 2p, 3s, 3p, 3d, ..., 4d, 4f; the He-like configurations $1s^2$, 1s2s, 1s2p, 1s3s, 1s3p, 1s3d, ..., 1s4d, 1s4f; plus the low-lying Li-like configurations $1s^2 2s$, $1s^2 2p$. For the elements H and He, the model only includes the fully-stripped ions.

GALAXY is a 0-D model; however, two lengths are considered in the calculation of radiation transfer. The first, y, is the average distance that photons travel to escape, while the second, z, is the length of plasma along a line-of-sight for which a calculation of the emergent intensity in a spectral line is required. In the calculations reported here y is taken as identical to z.

GALAXY uses a line trapping model to simulate the effect of reabsorption of line radiation. In this case the radiative rate (A-value) is reduced to account for the reabsorption as described by Rose (1995), with the difference that the escape factor now used in GALAXY differs from that reported in Rose (1995) by adopting the more accurate description described by Phillips et al (2008). Line trapping is included on all the electric-dipole allowed transitions from the ground states of H-like and He-like ions.

The line coincidence photopumping is calculated in GALAXY by including radiative excitation and de-excitation rates between the upper level β and lower level α ($\mathrm{R}^r_{\alpha\to\beta}$ and $\mathrm{R}^r_{\beta\to\alpha}$, respectively) by

$$\mathrm{R}^r_{\alpha\to\beta} = \mathrm{A}_{\beta\to\alpha} n_{ph} (\Omega_\beta/\Omega_\alpha)$$

$$\mathrm{R}^r_{\beta\to\alpha} = \mathrm{A}_{\beta\to\alpha} (1 + n_{ph})$$

where n_{ph} is the radiation model photon density covering the transition $\alpha \longleftrightarrow \beta$, and Ω_α and Ω_β are the degeneracies of levels α and β, respectively. For the case of interest here involving an internal source of photons where a transition $\chi \longleftrightarrow \delta$ is coincident with and pumps the transition $\alpha \longleftrightarrow \beta$ then we make the approximation

$$n_{ph} = 1/([n_\chi \Omega_\delta / n_\delta \Omega_\chi] - 1)$$

where n_χ and Ω_χ are the ion number density and degeneneracy of level χ, respectively. This method has been used in previous calculations of line coincidence photopumping, for example by Judge (1988) for the pumping of S I lines by H Ly-α radiation in the chromospheres of giant stars. The use of the above equations is approximate, and requires that the $\chi \longleftrightarrow \delta$ line (in our case the Na X 1s^2 ^{1}S – 1s2p ^{1}P transition) is optically thick and that this opacity-broadened line effectively overlaps the $\alpha \longleftrightarrow \beta$ line (in our case the Ne IX 1s^2 ^{1}S – 1s4p ^{1}P line). In the calculations reported here Na X 1s^2 ^{1}S – 1s2p ^{1}P is optically thick for cases showing a significant line enhancement ratio, and the line centres of the Na X 1s^2 ^{1}S – 1s2p ^{1}P and Ne IX 1s^2 ^{1}S – 1s4p ^{1}P transitions are close to the Doppler width of each line at the electron temperatures considered. Consequently we consider that our modelling of the line coincidence photopumping is adequate in approximately identifying the effect.

GALAXY calculates the emission intensity integrated over a spectral line along the line-of-sight in the plasma of length z using the expressions given in Rose (1995). The ratio of intensities has been calculated for the cases with and without photopumping, and that ratio is the line enhancement factor given in Figure 2. We believe that the approximations made in terms of the level of detail in the description of the atomic physics and of the radiation transfer are adequate to provide an indication of the effect of line coincidence photopumping in this situation. However, more accurate calculations would be needed to allow any observed line enhancements to be used reliably to predict plasma properties, which we will report in future publications.

We note that the line enhancement factors in Figure 2 are not very sensitive to the adopted electron temperature, T$_e$. For example, for a pathlength L = 10^{11} cm, increasing the temperature from that of maximum Ne IX fractional abundance in ionisation equilibrium, T$_e$ = 1.6×10^6 K, to 2.3×10^6 K, leads to a change in the line enhancement factor of less than 20% at an electron density of N$_e$ = 10^{11} cm^{-3}, decreasing to less than 15% at N$_e$ = 10^{13} cm^{-3}.

Calculation of synthetic flare spectrum with CHIANTI We have calculated a synthetic solar flare spectrum using the latest version (8.0.1) of the CHIANTI database, widely used by the solar physics community to model spectral emission lines from the outer regions of the solar atmosphere (see, for example, Keenan et al. 2017 and references therein). It is described in detail in Dere et al. (1997), with the most recent update discussed in Del Zanna et al. (2015). The flare spectrum has been generated using solar coronal abundances (Schmelz et al. 2012) appropriate to high temperature flare plasmas, as these are different to the photospheric values due to the First Ionisation Potential (FIP) effect (Meyer J-P et al. 1985).

Calculation of the 82.76 Å line wavelength The Lawrence Livermore team to provide some text (and figures if necessary) on the line wavelength calculation.