ON THE DETECTABILITY OF KEV-MEV SOLAR PROTONS THROUGH THEIR NONTHERMAL LYMAN-ALPHA EMISSION

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ABSTRACT

We investigate the intensity and timescale of nonthermal Doppler-shifted hydrogen Lα photon emission as diagnostics of 10 keV-10 MeV protons bombarding the solar chromosphere during flares. We determine the steady-state excitation and ionization balance of the proton beam, taking into account all important atomic interactions with the ambient chromosphere. For a proton energy flux comparable to the electron energy flux commonly inferred for large flares, we find Lα wing intensities orders of magnitude larger than observed nonflaring values. Our investigation of timescales for ionization and charge exchange leads us to conclude that over a wide range of values of mean proton energy and beam parameters, Doppler-shifted nonthermal Lα emission is a useful observational diagnostic of the presence of 10 keV-10 MeV superthermal proton beams in the solar flare chromosphere.

1. Introduction. Gamma-ray and hard X-ray observations of solar flares imply that, at energies $\geq$ 10 MeV, the number of of energetic protons exceeds that of energetic electrons by several orders of magnitude [6]. This is currently understood [4] to be the consequence of an acceleration mechanism (e.g., a stochastic Fermi mechanism) in which the acceleration rate is proportional to momentum, acceleration takes place in a tenuous medium (the corona), and the emission is produced when the energetic particles are stopped fully in a thick target (the chromosphere and photosphere). However, this mechanism operates effectively only if some particles are already accelerated above a threshold energy by some other mechanism. Orrall and Zirker [5] have shown that charge-exchange Lα emission may be useful for the detection of relatively low energy ($E < 1$ MeV) superthermal protons, which do not produce a significant level of nuclear emission. In this paper we extend the work of Orrall and Zirker to energetically significant values of beam flux, and address the question of the range of values of beam flux for which the intensity and timescale of Lα charge-exchange emission may fall into observationally relevant ranges.

2. Atomic Physics. To simplify our study of the emission of Lα by superthermal protons we represent the protons injected into the chromosphere by a vertical beam directed away from the observer. Some superthermal protons become superthermal hydrogen atoms in excited states, and subsequently radiate before they stop. Potentially relevant atomic processes that we have examined include charge exchange between beam protons and ambient hydrogen atoms, excitation of beam hydrogen atoms by collisions with ambient electrons, hydrogen atoms and protons, spontaneous radiative de-excitation of beam hydrogen atoms, stimulated radiative de-excitation of beam hydrogen atoms, collisional ionization of beam hydrogen

atoms by ambient electrons, protons and hydrogen atoms, and spontaneous radiative recombination of beam hydrogen atoms.

We have examined the relative importance of these various competing atomic processes, with the following conclusions. The dominant destruction process for superthermal beam protons is charge exchange with ambient chromospheric hydrogen atoms. Ionizing collisions of superthermal hydrogen atoms with ambient electrons, protons, and neutral hydrogen atoms are of comparable importance in creating superthermal protons. The main source of Lα emission is charge exchange from the proton beam. The dominant slowing process is Coulomb collisions with ambient electrons [7].

3. Computed Lα Spectra. Our chosen value of the hydrogen ionized fraction in our uniform chromospheric model atmosphere is guided by Orrall and Zirker, who used a detailed empirical model [8] to show that 10-1000 keV proton nonthermal Lα emission originates in the chromosphere. Our assumed 10% ionized fraction is an appropriate mean value. We have adopted a simple monoenergetic proton beam at input. The values of the input energy E_0 and the total input energy flux $F_E(0)$ are free parameters.

In Figure 1 we show the computed nonthermal Lα spectrum generated by monoenergetic proton beams of input energy flux $F_E(0) = 10^{11}$ erg cm^{-2} s^{-1} (an upper limit to plausible values), for values of E_0 ranging from 3 keV to 30 MeV If we examine a single curve, say for E_0 = 30 keV, we see a sharp

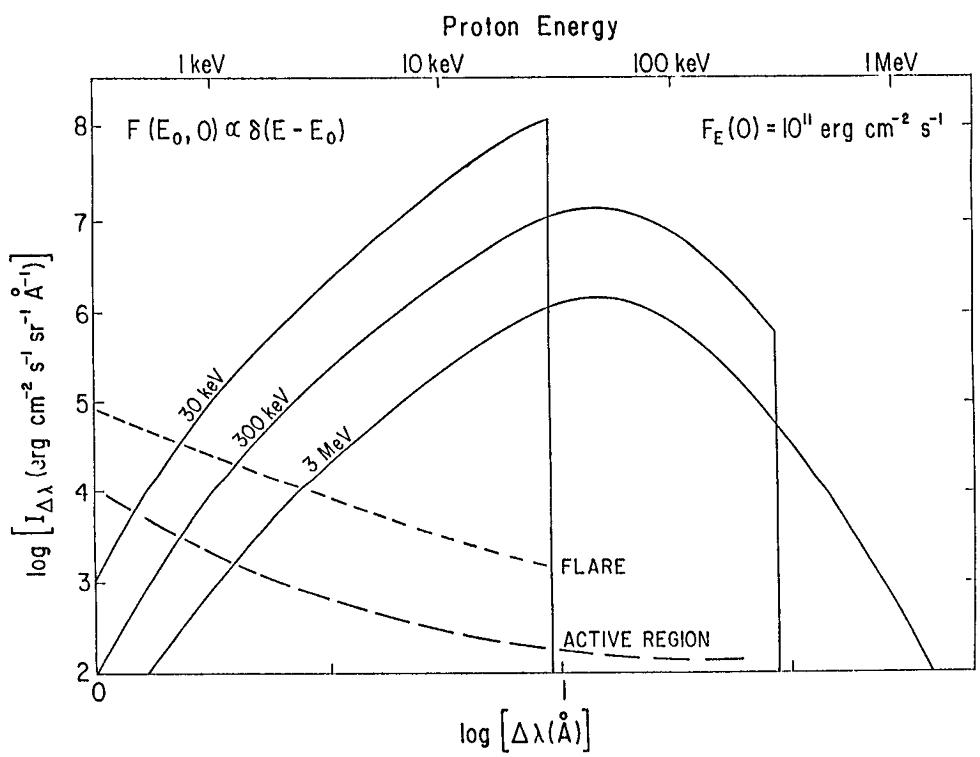

Fig. 1. - Theoretical nonthermal Lα spectra for protons of initial energy E_0.

peak in the spectrum at the wavelength shift $\Delta\lambda$ appropriate to the velocity of protons of initial energy E_0, corresponding to emission from near the top of the chromosphere. At lesser values of $\Delta\lambda$ the emission comes from slower protons that have penetrated some distance z into the target, where their velocity (and hence Doppler-shift) has dropped. If we consider the spectra in Figure 1 for E_0 = 300 keV and 3 MeV, we see that the curves peak somewhat below E = 100 keV (somewhat above $\Delta\lambda$ = 10 Å). This peak Lα intensity corresponds to the peak in the charge-exchange cross-section in this same energy range. It is interesting to compare the computed spectra to an observed solar active region Lα spectrum [3] and an observed (presumably thermal) solar flare Lα spectrum [2]. Throughout much of the energy range considered in Figure 1 the intensity of the computed nonthermal Lα emission exceeds the observed active region emission by several orders of magnitude.

4. Timescales. Our equilibrium computations of Lα emission will not be applicable unless the ionization structure of the chromosphere remains substantially unchanged within the time required for charge exchange. If the chromosphere becomes highly ionized within the collisional range of the protons, little charge exchange between superthermal protons and ambient hydrogen atoms can take place. Because recombination is several of orders of magnitude less efficient than charge exchange, per ambient particle, much less nonthermal Lα emission will be created if the atmosphere becomes ionized.

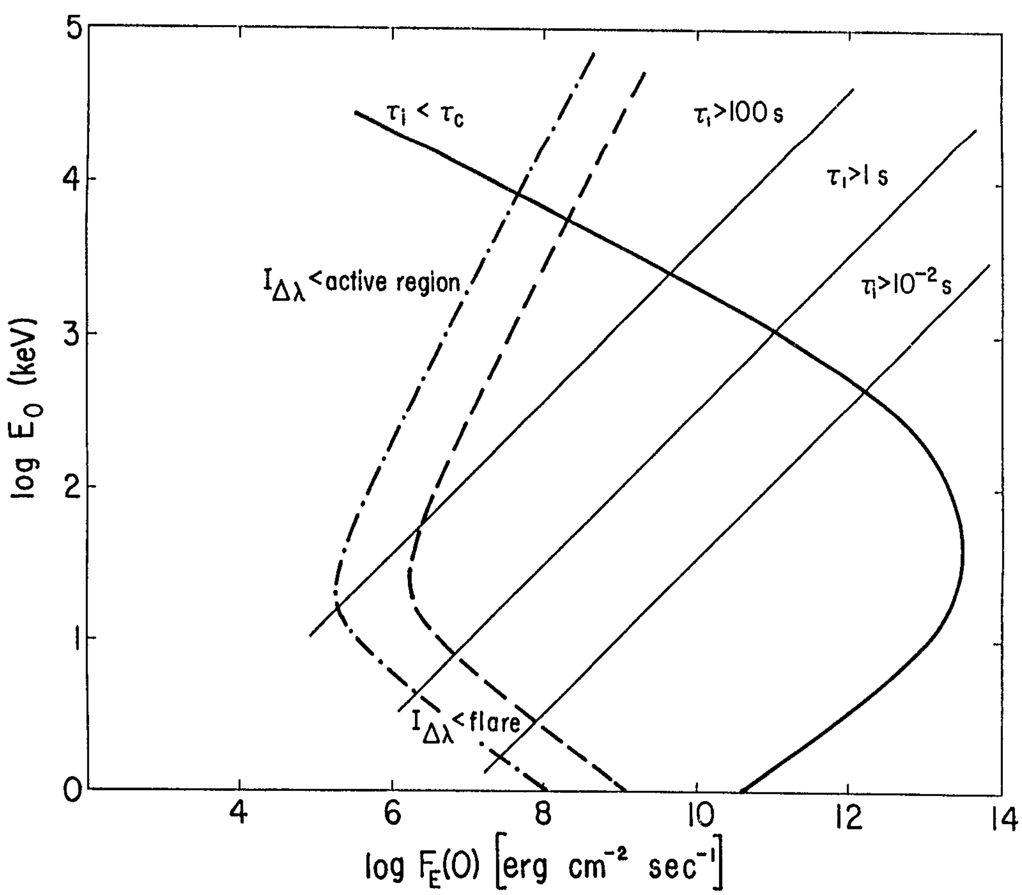

Fig. 2. The range of relevance of the equilibrium Lα spectra in Figure 1.

The range of relevance of the $L\alpha$ spectra of Figure 1 is explored in Figure 2. The thick solid curve is that for which the ionization timescale τ_i equals the charge exchange timescale τ_c. The thin lines indicate various values of τ_i. On the long-dashed curve the peak intensity of nonthermal $L\alpha$ emission equals that of observed flare $L\alpha$-wing emission. On the dot-dashed curve the peak computed intensity of nonthermal $L\alpha$ emission matches that of observed active-region $L\alpha$-wing emission. We see that at an energy of interest (say 100 keV), the intensity of nonthermal $L\alpha$ emission exceeds the observed active-region background for all $F_E(0)$ values above about 10^6 erg cm^{-2} s^{-1}, and the charge-exchange mechanism is effective up to around $F_E(0) \sim 10^{13}$ erg cm^{-2} s^{-1}. Over this range of $F_E(0)$ values the ionization time ranges from about 1000 s to very small values. Obviously at the lowest detectable intensities the equilibrium calculation given above is physically relevant throughout the duration of typical flares; at the high end of the $F_E(0)$ range, the duration of validity becomes inconsequentially small. Figure 2 also serves to show that at input proton energies above about 10 MeV and below about 1 keV the equilibrium calculation is not both physically and observationally relevant at any value of the total energy flux.

5. Conclusions. We conclude that if the sun's chromosphere is bombarded suddenly from above by superthermal protons of energy 10 keV - 1 MeV, with energy fluxes consistent with the hypothesis that such protons are a significant component of the population of superthermal particles in flares, charge exchange would lead to an intense but brief burst of Doppler-shifted $L\alpha$ emission. At much lower proton flux levels the emission would still exceed preflare background, but last much longer. In other work [1] we consider power-law and thermal forms of the input proton energy spectrum, the generation of emission in the hydrogen $H\alpha$ line, and the details of the atomic physics.

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