POSITRON ANNIHILATION LINE FROM THE 15 NOVEMBER 1991 FLARE

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Abstract

Time history of the positron annihilation line produced during 15 November 1991 flare (X1.0/3B) is calculated from the precipitation rate and the energy spectrum of energetic ions estimated from prompt nuclear lines and neutron capture line. It is shown that integration time dependence of the integrated counts can be interpreted by a model of Kawabata *et al.* (1994), *i.e.* more than half of positrons annihilates in coronal flare loops with a density of 10^{12}–10^{13} cm^{-3} and with a temperature of 10^6–3×10^6 K. The number of protons impinging on the photosphere with energies > 30 MeV is estimated to be 1.5×10^{32} and the energy of these protons is 9×10^{27} erg. When we extrapolate the energy spectrum of protons to lower energy, the total energy of energetic nuclei impinging on the photosphere can be estimated to be 10^{30} erg.

1. Introduction

The gamma-ray spectrometer on board Yohkoh has detected the positron annihilation line from a flare on 15 November, 1991. The time variation of the annihilation line exhibited a delay of the starting time and a gradual decay compared with prompt nuclear deexcitation line and electron bremsstrahlung components. Kawabata *et al.* (1994, hereafter Paper I) have calculated the integrated counts of 511 keV band photons as a function of integration time for this event. They have suggested the following. (1) the most important positron emitting mechanism for this event is the $e^+ - e^-$ pair emission from $^{16}\mathrm{O}^{*6.052}$. (2) most positrons are produced in the photosphere at the density of 10^{15} cm^{-3}. (3) at least half of positrons annihilates in the coronal region with a density of 10^{12}–10^{13} cm^{-3} at the temperature of

8×10^5–3×10^6 K. (4) a probable annihilation region is coronal flare loop system observed in white-light. These authors were, however, dealing only the relative variation and not discussing the absolute values of the counts. These authors have also not taken into account a correction of accumulation times of gamma-ray lines.

In this paper, we discuss quantitatively the annihilation of positrons in the flare adopting parameters obtained from prompt gamma-ray lines and the neutron capture line and also the time difference of the actual integration time between the annihilation line and prompt nuclear lines. By these improvement of the analysis, the conclusion in Paper I has not changed.

2. Observations

Yohkoh has observed an X-class flare at 22:37 UT on 15 November, 1991. The flare location was S12W13, and the GOES class and Hα importance were X1.0 and 3B, respectively. The flare associated prompt gamma-ray lines, Be and Li lines due to $\alpha - \alpha$ reactions, the neutron capture line at 2.2 MeV and the positron annihilation line at 511 keV(Yoshimori *et al.* 1994). The primary-data output of the Yohkoh gamma-ray spectrometer is a 128-channel pulse height spectrum from 0.4 to 100 MeV every 4 s. The instrument description has been given in detail by Yoshimori *et al.* (1991). The 4–7 MeV band emission is dominated by prompt nuclear deexcitation lines of ^{12}C and ^{16}O at 4.44 and 6.13 MeV. Gamma-ray counting rates in the 4–7 MeV band started to increase slightly at 22:37:28–22:37:32 UT, strongly enhanced at 22:37:44–22:37:48 UT, attained to the maximum counting rate at 22:37:48–22:37:52 UT, and lasted until 22:37:58 UT. The 511 keV line is apparent above the continuum in the spectrum of 22:37:50–22:37:54 UT but can not be found in the spectrum of 22:37:46–22:37:50 UT (Paper I). It indicates a delay of annihilation line emission compared with the precipitation of energetic nuclei. The emission in 502–532 keV band exhibited also a long decay compared with the 4–7 MeV band, indicating a gradual decay of the positron annihilation line compared with decay of the precipitation rate of energetic nuclei.

The 511 keV line fluence between 22:37:50 and 22:38:14 UT is (6.7 ± 2.2) photons cm^{-2}. Comparison of two line widths obtained from the solar flare and background spectra enable us to establish an upper limit to the intrinsic width of the solar positron annihilation line. The upper limit is 20 keV in FWHM. This allows us to set the upper limit to the temperature in the annihilation region as 3×10^6 K.

The ratio of fluence of 4.44 and 2.22 MeV line gives the acceleration parameter $\alpha T = 0.009 \pm 0.002$ (α is the acceleration rate and T is the escape time from the acceleration region) in stochastic acceleration (Ramaty 1979) in the thick target model. The number of protons impinging on the photosphere can be obtained from the ^{12}C and ^{16}O line fluences at 4.44 and 6.13 MeV. The method gives 1.1×10^{32} as a total number of protons impinging on the photosphere.

3. The Time Variation of Annihilation Line

We have calculated the time variation of counting rate of 511 keV band assuming that the precipitation rate of energetic nuclei is proportional to the counting rate of the prompt gamma-rays(4–7 MeV) for several values of positron lifetime. Production yields of positron emitters depend on the energy spectrum of the incident energetic nuclei and interaction models, and are given by Kozlovsky, Lingenfelter, and Ramaty (1987). We have estimated the production yields in the thick target model for $\alpha T = 0.009$ by extrapolating their result, representing the logarithm of production yields by a polynomial of order 3 of $\log \alpha T$.

As is discussed in Paper I, positron emitters are produced in the photospheric level of the density of 10^{15} cm^{-3} by precipitation of energetic nuclei. If we assume a uniform magnetic field in the photosphere, the half of positrons produced penetrates downward and annihilates in the photosphere after the deceleration. The remainder of positrons moves upward and escapes to the corona without significant loss of energy. The ratio of the number of positrons moving downward to upward depends on the configuration of the magnetic field in the production layer of positron emitters and below. Positrons escaping to the corona can impinge again the photosphere by mirror effect or at the other footpoint. Another plausible situation is that these positrons are trapped and annihilate in the magnetic loop spatially in the corona. The ratio of the number of positrons annihilating in the photosphere to that in the magnetic loop depends on the configuration of the magnetic field, the density, wave-particle interactions, and so on in the loop.

Figure 1 illustrates integration time dependence of the calculated integrated-counts for three cases. The numeral at the top of each panel implies the calculated fluence integrated from 22:37:50 and 22:38:14 UT. The top panel of the figure is obtained by assuming that positrons annihilate with very short lifetime. The delay of the onset and the gradual decay of the annihilation line can not be interpreted in this model. The middle and bottom panel of the figure illustrate the case of the positron lifetime of 5 and 10 seconds, respectively. The calculated lines in these panels show a good agreement with observations. We have tried the calculation for several parameters and have come to a conclusion that at least the half of positrons must be annihilated with a lifetime of 5–50 s.

When positrons annihilate in the photosphere, the lifetime of positrons becomes the order of the travel time of MeV positrons to move the scale height of the photosphere. Then such a long lifetime as 5–50 s implies the annihilation in the corona. We have to also assume the free annihilation in the magnetic loop in order to get such a long lifetime. If positronium are formed, only two among eleven photons produced by positronium annihilation contribute to the 511 keV line and the other photons form continuum below 511 keV and then we cannot expect an agreement with observations.

4. Discussion and Conclusions

The temperature of the annihilation region in the corona must be higher than 10^6 K for free annihilation according to the calculation by Bussard, Ramaty, and Drachman (1979) and must be less than 3×10^6 K from the observed line width of the annihilation line. From the figure in Crannell *et al.* (1976), lifetime of positrons against the annihilation is given by $5 \times 10^{13}/n_e$ s by taking into account Coulomb correction. If we put the lifetime of positrons as 5 s, the electron density of the annihilation region becomes 10^{13} cm^{-3}.

Hudson *et al.* (1992) have observed a white-light flare of a loop like structure with Soft X-ray Telescope on Yohkoh. They have suggested that sufficient material evolved into the corona to provide enough opacity at an altitude of 8,000 km. The white-light image suggests that the length of a white-light loop is about 24,000 km. The coronal loops will be the most likely positron annihilation region.

From these considerations, we come to the following conclusions. The most likely annihilation region is the photosphere of density of 10^{16} cm^{-3} and a dense coronal loop at the temperature of $10^6 - 3 \times 10^6$ K. At least 50 % of positrons annihilates in the dense coronal loop. The density of coronal annihilation region obtained is 10^{12}–10^{13} cm^{-3}. The total energy of these protons of > 30 MeV is 7×10^{27} erg. When we extrapolate the energy spectrum to less than 1 MeV, the total energy of energetic nuclei including α particles becomes 1.4×10^{30} erg.

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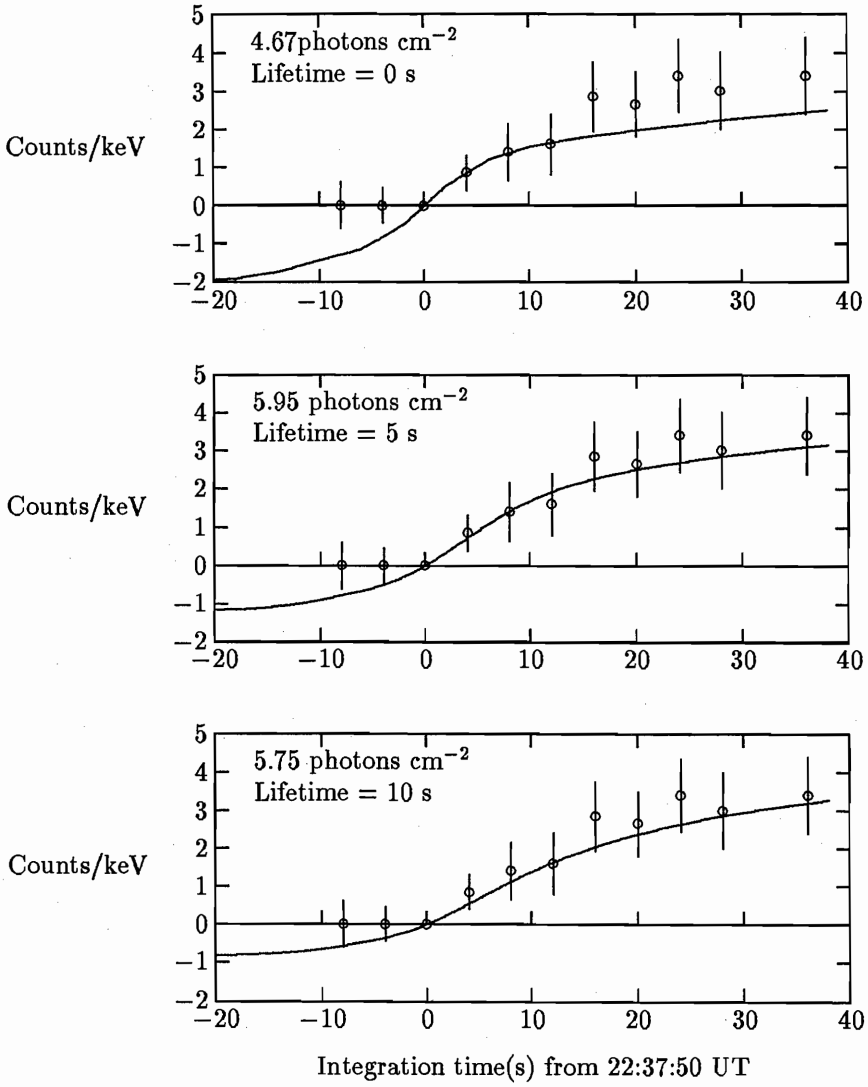

Fig. 1. Time integrated counts of the positron annihilation line