GAMMA RADIATION AND PHOTOSPHERIC WHITE-LIGHT FLARE CONTINUUM

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Abstract. Recent gamma-ray observations of solar flares have provided a better means for estimating the heating of the solar atmosphere by energetic protons. Such heating has been suggested as the explanation of the continuum emission of the white-light flare. We have analyzed the effects on the photosphere of high-energy particles capable of producing the intense gamma-ray emission observed in the 1978 July 11 flare. Using a simple energy-balance argument and taking into account hydrogen ionization, we have obtained the following conclusions:

1. Heating near \( r_{5000} = 1 \) in the input HSRA model atmosphere is negligible, even for very high fluxes of energetic particles.

2. Energy deposition increases with height for the inferred proton spectra, and does not depend strongly upon the assumed angle of incidence. The computed energy inputs fall in the range 10–100 ergs \( \text{cm}^{-2} \text{s}^{-1} \) at the top of the photosphere.

3. H\(^+\) continuum dominates for column densities as small as \( 10^{22} \text{cm}^{-2} \), but at greater heights hydrogen ionizes sufficiently for the higher continua to dominate the energy balance.

4. The total energy deposited in the 'photospheric' region of H\(^+\) dominance could be within a factor of 3 of the necessary energy deposition, by comparison with the white-light flare of 1972 August 7, but the emergent spectrum is quite red so that the intensity excess in the visible band is insufficient to explain the observations.

In summary, it remains energetically possible, within observational limits, that high-energy protons could cause sufficient heating of the upper photosphere to produce detectable excess continuum, but emission from the vicinity of \( r = 1 \) is not significant.

1. Introduction

White-light continuum emission occurs in solar flares only in association with the most intense or energetic phenomena. Such events have only been rarely recorded, beginning with the 'first' solar flare observed visually by Carrington and by Hodgson in 1859, and photographic or spectrographic data exist only for a very few events. The best-observed single event was undoubtedly the 1972 August 7 flare (Rust and Hegwer, 1975); Švestka (1976) has given the most recent review of observational material.

At present we have no compelling theory for the phenomenon, nor even a firm idea about the emission mechanism. Of the theories suggested, those that attempt to relate the white light to energetic particles – protons or electrons – have been the most attractive because of the occurrence of hard X-radiation, gamma-radiation, and solar cosmic-ray production in these major events. Furthermore, such models resemble at the simplest level the 'well-understood' mechanism of the terrestrial aurora. Finally, the preliminary theories that have been put forward for protons (Švestka, 1970; Najita and Orrall, 1970) and electrons (Hudson, 1973; Lin and Hudson, 1976) have been encouraging. Nevertheless, three cautionary notes should be considered.
(i) The theories have only been approximate, schematic treatments, partly because of lack of knowledge of physical conditions.

(ii) The observational capabilities have not progressed to the point where predictive theories are worthwhile, partly because of the brief duration of the white-light continuum and its lack of predictability.

(iii) The apparent simultaneity between high-energy phenomena and white-light continuum may be deceptive, since all known phenomena will generally occur in one of the white-light flares in any case, given their very energetic nature.

Since conception of these particle-related theories, new data have been obtained. Specifically we now have observations of a coincident white-light flare (Deszö et al., 1980) and gamma-ray burst (Hudson et al., 1980). Gamma-radiation, especially lines that may be directly excited, give information about energetic protons that is exactly analogous to that derived from bremsstrahlung X-radiation for energetic electrons. Thus for the first time a quantitative assessment of the energy deposition in the flare region can be attempted; to carry out this assessment requires a more quantitative theory than that previously available.

In recent years, as a result of the Skylab data (Sturrock, 1980), considerable effort has gone into understanding the mechanisms of heating near the temperature minimum (Machado et al., 1978; Emslie and Machado, 1979; Machado et al., 1980) that flare model atmospheres require. These analyses have not attempted to study the details of the atmospheric disturbance but have instead relied upon tying the theory to the semi-empirical model atmospheres derived from emission line profiles. Although this procedure does relate back to observations, it is an indirect relationship in the sense that the model data may or may not refer to the appropriate conditions – the Machado and Linsky (1975) models, for example, probably do not accurately describe the conditions in the impulsive phase when the high pressures needed for these models may not yet have developed.

A need therefore exists for a self-consistent assessment of particle bombardment theories, in which no prior restrictions are placed on the physical conditions in the atmospheric model. This approach may not be valid in the chromosphere (Hudson, 1973) because of the strongly transient nature of the observed phenomena. In the photosphere, however, a simple theory of the continuum based upon LTE (Emslie and Machado, 1979) and realistic particle energies derived from the recent data should be reliable. In this paper we extend the earlier proton-bombardment theory using this approach to analyze the conditions under which appreciable white-light continuum can be produced. The Solar Maximum Mission should produce new data relating white-light continuum with gamma-ray spectroscopy that can test the results of this theory.

2. Proton Spectrum and Propagation

The new gamma-ray observations have made it possible to estimate the proton fluxes in the solar atmosphere without need for reference to the interplanetary