

CHROMOSPHERIC DENSITY AND HEIGHT MEASUREMENTS OF THE 2002-FEB-20 FLARE OBSERVED WITH RHESSI

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ABSTRACT

We present the first chromospheric density and height measurements made with the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spacecraft during the flare of 2002-Feb-22, 11:06 UT. Thanks to the high energy resolution of the germanium-cooled hard X-ray detectors on RHESSI we can measure the flare source positions with a high accuracy as a function of energy. Using a forward-fitting algorithm for image reconstruction, we find a systematic decrease in the altitudes of the source centroids $z(\varepsilon)$ as a function of increasing hard X-ray energy ε , as expected in the thick-target bremsstrahlung model of Brown. The altitude of hard X-ray emission as a function of photon energy ε can be characterized by a powerlaw function in the $\varepsilon = 15 - 50$ keV energy range, viz. $z(\varepsilon) \approx 2.3(\varepsilon/20 \text{ keV})^{-1.3}$ Mm. Based on a purely collisional 1-D thick-target model, this height dependence can be inverted into a chromospheric density model $n(z)$, which follows the powerlaw function $n_e(z) = 1.25 \times 10^{13} (z/1 \text{ Mm})^{-2.5} \text{ cm}^{-3}$. This density is comparable with models based on optical/UV spectrometry in the chromospheric height range, while at a height of $h \approx 1000 - 2500$ km, it is more consistent with the “spicular extended-chromosphere model” inferred from radio sub-mm observations. In coronal heights of the flare loop, the RHESSI inferred densities are comparable with soft X-ray and radio observations.

Key words: Sun : corona – Sun : chromosphere – hard X-rays – RHESSI observations .

1. INTRODUCTION

Here we measure for the first time hard X-ray source altitudes with the RHESSI spacecraft, which has an unprecedented energy resolution thanks to the germanium-cooled detectors, and thus is expected to provide the most accurate spectral height measurements. The reason is because the observed height distribution of hard X-ray emission, which is a convolution of the electron injection spectrum, the bremsstrahlung cross-section, and the instrumental

spatial/energy resolution, can most accurately be modeled for a high energy resolution. We model the spatial distribution of hard X-ray sources observed with RHESSI during the 2002-Feb-20 flare according to the theoretical model of thick-target bremsstrahlung. A more detailed account of the theory and data analysis is given in Brown, Aschwanden, & Kontar (2002) and Aschwanden, Brown, & Kontar (2002).

2. DATA ANALYSIS

One of the first solar flares observed with the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) occurred on 2002-Feb-20, 11:06 UT. The flare location (N16 W80) is close to the solar west limb, so that the north-south directed flare loop has a loop plane nearly perpendicular to the line-of-sight. This favorable geometry minimizes projection effects and allows us to investigate the vertical structure of the energy loss regions in this flare loop seen face-on. We reconstruct RHESSI images in the energy range of 10 to 60 keV, in energy steps of 1 keV. Because the hard X-ray images show a simple double source we apply a forward-fitting method with two gaussian sources and measure for each the centroid locations (x_i, y_i) as function of the hard X-ray photon energy ε_i , which yields the distance $r(\varepsilon_i) = \sqrt{x_i^2 + y_i^2}$ from Sun center as a function of energy ε_i . We choose a powerlaw function to fit the observed source altitudes $z(\varepsilon)$ as a function of the energy ε ,

$$z(\varepsilon) = r(\varepsilon) - r_0 = z_0 \left(\frac{\varepsilon}{20 \text{ keV}} \right)^{-a}. \quad (1)$$

In the high-energy limit ($\varepsilon \mapsto \infty$) this powerlaw function yields as asymptotic limit a zero height ($z \mapsto 0$), which we can associate with the solar surface at the location of the flare loop footpoints. This powerlaw function has three free parameters, the source height z_0 at 20 keV, the reference level r_0 , and the powerlaw slope a . We determine these three parameters from a least-square fit (with the Powell minimization method) to the observed values $r(\varepsilon_i)$ (Fig.1 right panels). We fit only over the energy range $15 \text{ keV} < \varepsilon_i < 50 \text{ keV}$, which is the energy range

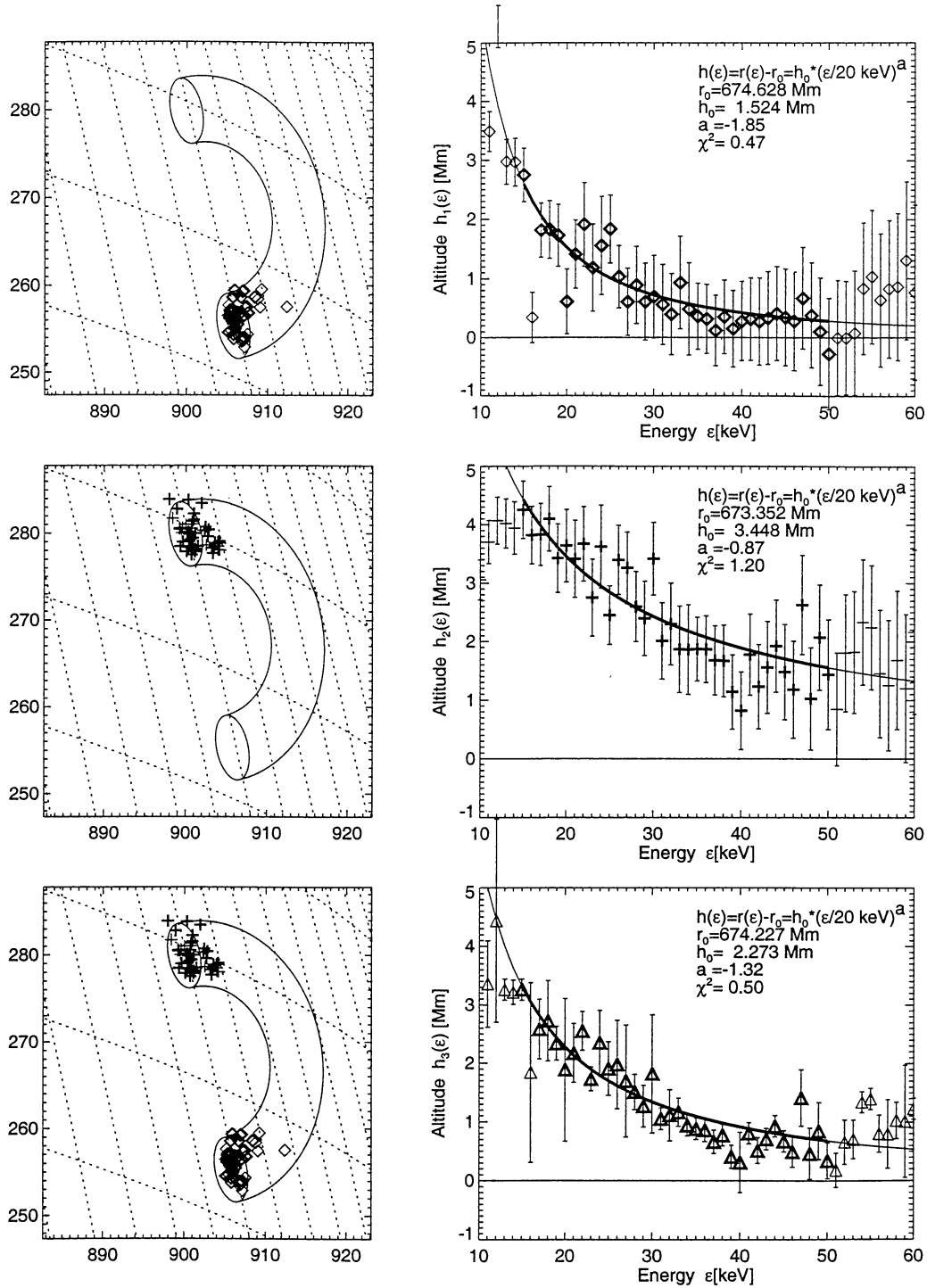


Figure 1. Height measurements of the centroids of the gaussian fits to the hard X-ray sources. The spatial location of the source centroids are shown in the left side, the altitudes as functions of energy in the right panels. Measurements at the southern footpoint are shown in the top panels, at the northern footpoint in the middle panels, and combined measurements in the bottom panel. The error bars of the height measurements were estimated from Poisson statistics in the cases of single footpoints, or from the differences in the case of combined footpoints. The curves indicate powerlaw fits, marked with thick linestyle in the energy range of the fit (15-50 keV). The best-fit parameters are also indicated.

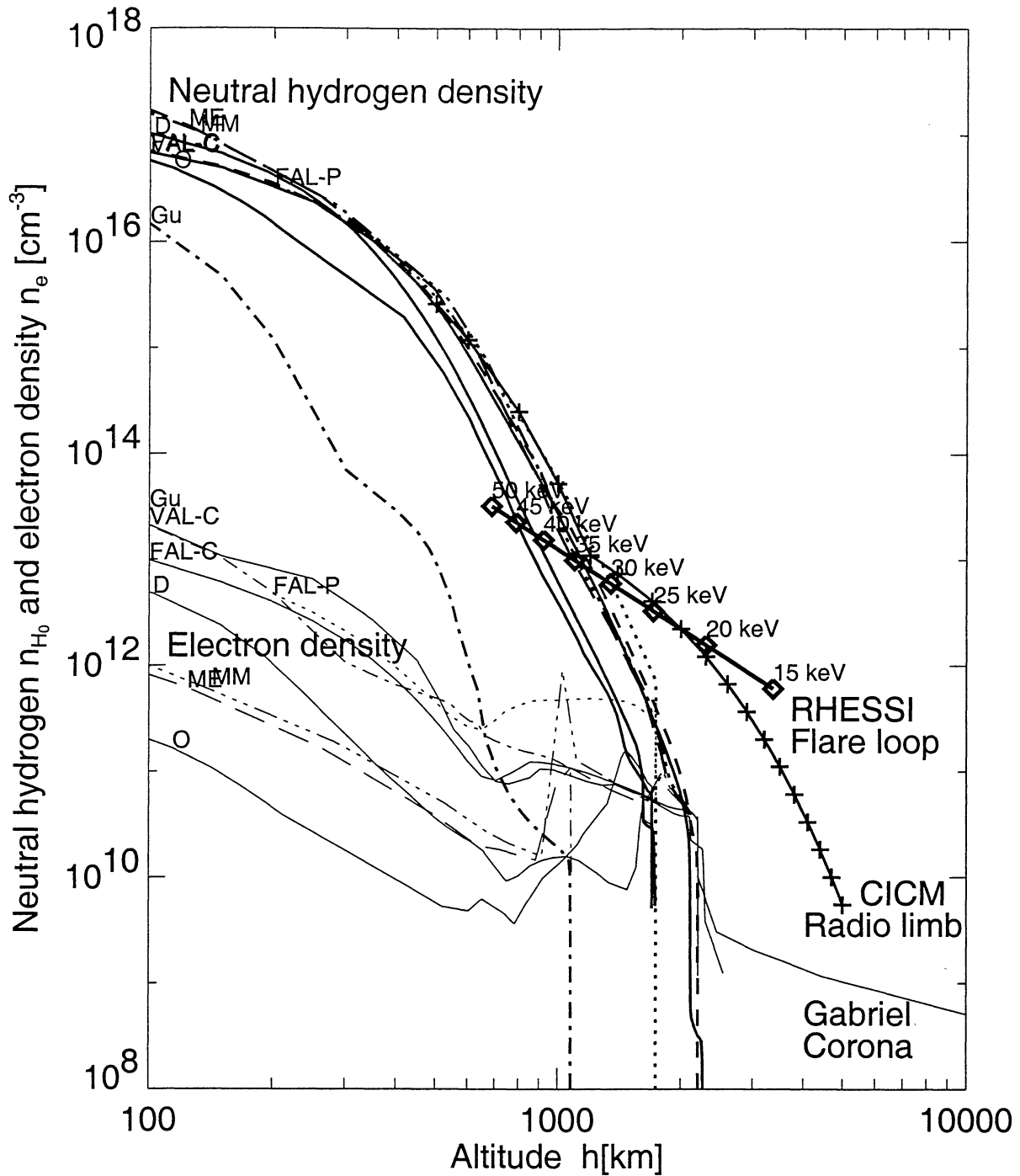


Figure 2. A compilation of chromospheric and coronal density models: VAL-C = Vernazza, Avrett, & Loeser (1981), model C; FAL-C = Fontenla, Avrett, & Loeser (1990), model C; FAL-P = Fontenla, Avrett, & Loeser (1990), model P; G = Gu, Jefferies et al. (1997); MM = Maltby et al., (1986), model M; ME = Maltby et al., (1986), model E; D = Ding & Fang (1989); O = Obridko & Staude (1988); Gabriel = Gabriel (1976), coronal model; CICM = Caltech Irreference Chromospheric Model, radio sub-millimeter limb observations (Ewell et al. 1993), RHESSI flare loop (this work).

that exhibits clear double-footpoint morphology. Averaging the altitudes from both footpoints (and adjust them to the same reference height) we find an average distance of $r_0 = 674.2$ Mm to solar disk center, a height of $z_0 = 2.3$ Mm at 20 keV, and a powerlaw slope of $a = 1.32$ (Fig. 1 bottom right). The powerlaw dependence $z(\varepsilon)$ (Eq. 1) deduced from the observations can be inverted, to give $\varepsilon(z) = 20(z/z_0)^{-1/a}$ [keV].

The energy loss region spreads for every photon energy ε over some height range, which can be characterized by the Incomplete Beta function $dI/dz(\varepsilon, z)$ according to the thick-target model (Brown et al. 2002). The height of the maximum energy loss for a given photon energy ε , i.e. the peak of the Incomplete Beta function $dI/dz(\varepsilon, z)$, depends on the parameters n_0 and b of the chromospheric model,

$$n(z) = n_0 \left(\frac{z}{z_0} \right)^{-b} \quad (2)$$

as well as on the spectral slope δ of the hard X-ray photon spectrum (Brown et al. 2002). We calculate the flux distributions $dI/dz(\varepsilon, z)$ for the observationally determined spectral slope $\delta = 4.9$ and vary the free parameters n_0 and b of the chromospheric model until we find a best match between the maximum of the Incomplete Beta function $dI/dz(\varepsilon, z)$ and the observed heights. We find a best fit for the parameters $b = 2.5$ and a density constant $n_0 = 1.56 \times 10^{12} \text{ cm}^{-3}$. Thus our best-fit density model is

$$n(z) \approx 1.25 \times 10^{13} \left(\frac{z}{1 \text{ Mm}} \right)^{-2.5} [\text{cm}^{-3}]. \quad (3)$$

3. DISCUSSION

Previous altitude measurements of hard X-ray sources (Kane 1983; Takakura et al. 1986; Matsushita et al. 1992, Aschwanden et al. 1999) exhibited a systematically higher altitude (up to 10,000 km higher) than measured here with *RHESSI*, which is probably subject to large errors due to the unknown reference height of the solar surface beneath the flare loop footpoints and due to the substantially poorer energy resolution of the used instruments (e.g. *Yohkoh/HXT*).

We compare the densities $n_e(h)$ we inferred from *RHESSI* as a function of height h with other chromospheric models (Fig. 2), which include a group of hydrostatic model calculations based on optical and UV spectroscopy (VAL and FAL models), as well as radio-based measurements of the solar limb during a solar eclipse in sub-millimeter wavelengths (Ewell et al. 1993), which led to the so-called *Caltech Irreference Chromospheric Model (CICM)*. What is special about the CICM empirical model is that it shows an extended chromosphere that shows an excess density up to a height of $h \approx 6000$ km, compared with hydrostatic coronal models (e.g. Gabriel 1976), probably due to the ubiquitous presence of spiculae, which are not part of hydrostatic calculations. Interestingly, the *RHESSI*-inferred electron densities in the 20-40 keV energy range match closely the radio sub-millimeter observations.

Of course, the *RHESSI* density measurements apply to a flare loop, which might have a higher density at the altitudes of interest due to chromospheric evaporation. However, most of previous observations and hydrodynamic simulations show typical densities of $n_e \approx 10^{11} \text{ cm}^{-3}$ for flare loops filled with heated chromospheric plasma. If we average the *RHESSI*-inferred density over the entire flare loop, we obtain $n_e \approx 0.6 - 2.7 \times 10^{11} \text{ cm}^{-3}$, depending where we set the lower height limit ($h_{min} = 2 - 6$ Mm). These values compare favorably with other measurements, such as determined from soft X-ray emission measures with *Yohkoh/SXT* (Aschwanden et al. 1997a), with collisional deflection times estimated from trapping delays with *BATSE/CGRO* (Aschwanden et al. 1997b), or from the plasma frequency of radio bursts that show slowly-drifting decimetric cut-offs, interpreted as signature of chromospheric evaporation (Aschwanden & Benz 1997), all yielding average flare loop densities of $n_e \approx 10^{11} \text{ cm}^{-3}$.

These measurements and quantitative modeling have demonstrated that the Brown (1971) thick-target model is a good description of the hard X-ray height structure for reasonable target densities, and that this method provides a new diagnostic tool of chromospheric densities that complements optical/EUV spectroscopy.

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