ϵ Canis Majoris and the Ionization of the Local Cloud

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Using the EUV (70 – 730 Å) spectrum of the brightest EUV source, ϵ CMa taken with the *Extreme Ultraviolet Explorer Satellite* (*EUVE*) and simple models that extrapolate this spectrum to the Lyman edge at 912 Å, we have determined the local interstellar hydrogen photoionization parameter, Γ, solely from this B2 II star to be 1.1×10^{-15} s^{-1}. This figure is a factor of 7 greater than previous estimates of Γ calculated for *all* nearby stars combined (Bruhweiler & Cheng 1988). Using measured values of the density and temperature of neutral interstellar hydrogen gas in the Local Cloud, we derive a particle density of ionized hydrogen, $n(H^+)$, and electrons, n_e, of 0.015 – 0.019 cm^{-3} assuming ionization equilibrium and a helium ionization fraction of less than 20%. These values correspond to a hydrogen ionization fraction, X_H from 19% to 15%, respectively.

1. Introduction

One of the surprising results of the all-sky photometric survey carried out by *EUVE* was the discovery that the B2 II star ϵ CMa was the brightest source in the EUV sky (Vallerga, Vedder, & Welsh 1993). Most of the EUV flux from ϵ CMa was detected in the "tin" filter bandpass (500 – 700 Å), which is very susceptible to absorbing interstellar hydrogen. At 100 counts per second in the tin band, ϵ CMa was over an order of magnitude brighter than β CMa, HZ 43, and Sirius B. It was already known that in the direction of β CMa (B1 II–III) an "interstellar tunnel" of very low interstellar neutral hydrogen column extends as far as $\sim$300 pc and includes the star ϵ CMa at 187 pc (Welsh 1991). It was totally unexpected that the slightly later type star, ϵ CMa, would have a brighter Lyman continuum flux at Earth than the earlier type β CMa, since small temperature differences have such a large effect on the Wien tail of the Planck function. It was pointed out by Vallerga, Vedder, & Welsh (1993) that such a large flux in the EUV would affect the ionization state of the Local Cloud, but the single flux measurement in the tin bandpass could not constrain the stellar models and interstellar medium (ISM) absorption well enough to derive a spectrum that could be used to calculate the local ionization rate. However, the EUV spectrum of ϵ CMa taken using the spectrometers aboard *EUVE* (Cassinelli et al. 1994) effectively represents the local stellar EUV radiation field above 500 Å. From this EUV spectrum a photoionization rate of the local ISM can then be derived. A more detailed approach to this problem can be found in Vallerga & Welsh (1995).

2. Observations and Data Analysis

Observations of ϵ CMa with the three spectrometers aboard *EUVE* took place in January, 1993, and covered the entire EUV range from 70 to 730 Å. Details of the observation and reduction to the one-dimensional spectrum are given in Cassinelli et al. (1994). The long wavelength fluxed spectrum of ϵ CMa at Earth is shown in Figure 1. Because the source is so bright, the errors in the intensity for each bin are dominated by systematic rather than statistical effects, and the relative errors are estimated to be

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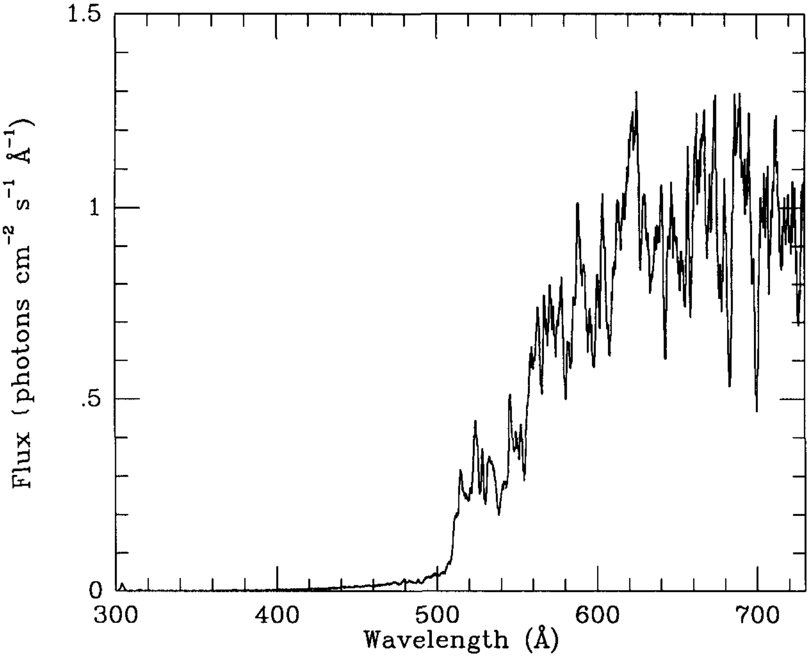

FIGURE 1. The flux density versus wavelength of ϵ CMa at the Earth as observed by *EUVE* showing the intense emission above the neutral helium edge at 504 Å.

less than 10%. Errors in the derived absolute flux density depend on the effective area calibration of *EUVE* and await a complete analysis of in-orbit calibration data from many more stars. Assuming the instrument response is unchanged from prelaunch values, the absolute effective areas will be accurate to 25%.

The hydrogen photoionization parameter,

$$\Gamma = \int_0^{912\,\text{Å}} N_\lambda \; \sigma_{\rm H} d\lambda \tag{2.1}$$

is the radiation field flux, N_λ (photons cm^{-2} s^{-1} Å^{-1}), weighted by the hydrogen cross section, $\sigma_{\rm H}$ (cm^2).

The total ionizing flux from ϵ CMa, as well as the corresponding hydrogen photoionization parameter, are given in Table 1. This includes both the measured values derived by integrating the flux using only the measured spectrum from 400 to 730 Å as well as the unobserved values derived by integrating the extrapolated spectrum of an absorbed stellar blackbody from 730 to 912 Å (T = 17300 K, $N_{\rm H} = 9 \times 10^{17}$ cm^{-2}). The errors in the extrapolated numbers were estimated by using the extreme curves plotted in Figure 2 and amount to no more than 6% of the total ionizing photon flux and 9% of the photoionization parameter. Also shown in Table 1 is the flux and ionization parameter at the edge of the Local Cloud assuming all of the observed absorption toward ϵ CMa is due to the cloud itself. Not shown in Table 1 is the absolute error of 25% because of the uncertainty of the *EUVE* effective area.

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TABLE 1. Ionizing flux and hydrogen photoionization rate from ϵ CMa

	At Earth	Local Cloud Surface†
Integrated Flux (photons cm^{-2} s^{-1})‡		
Measured (504–730 Å)	169	2150
Extrapolated (730–912 Å)	152 ± 20	11000 ± 3000
Total (504–912 Å)	320 ± 20	13150 ± 3000
Photoionization Rate, Γ_{H^0} (s^{-1})‡		
Measured (504–730 Å)	4.1×10^{-16}	5.9×10^{-15}
Extrapolated (730–912 Å)	$6.8(\pm 1.1)\times10^{-16}$	$5.6(\pm 1.6)\times10^{-14}$
Total (504–912 Å)	$1.1(\pm 0.1)\times10^{-15}$	$6.2(\pm 1.6)\times10^{-14}$

† Assumed that all absorption is due to a Local Cloud and the total neutral hydrogen column density is $9\times10^{17}cm^{-2}$.

‡ Errors shown are only those resulting from the extrapolation of the spectrum to the Lyman edge. The absoute flux is only known to 25% because of the calibration of the effective area of *EUVE*. Statistical errors are insignificant.

The value of Γ_H in the Local Cloud resulting from ϵ CMa is a factor of 6.9 greater than that predicted for the sum of all the bright EUV emitting stars known or predicted by Bruhweiler & Cheng (1988). Previous authors, although cognizant of the low interstellar column to ϵ CMa, did not realize that ϵ CMa is brighter than β CMa in the Lyman continuum by a factor of ~ 16 even though the effective temperature of β CMa (B1 II–III) is 4000 K hotter than ϵ CMa (B2 II). With the *EUVE* all-sky photometric survey now complete from 70 to 760 Å, we can now rule out the possibility of another unknown, constant *stellar* source of Lyman continuum radiation that would dominate the EUV radiation field.

The *diffuse* contribution to the hydrogen ionization parameter of emission from the 10^6 K gas surrounding the Local Cloud was calculated to be small when compared to stellar sources (Cheng & Bruhweiler 1990). The possibility exists, however, that the gas in the conductive interface at a temperature of $\sim10^5$ K between the Local Cloud and the surrounding hot, ionized gas, will dominate the EUV radiation field because of strong EUV emission lines and the large solid angle of this postulated source. Slavin (1989) developed a model of this interface and predicted a diffuse EUV spectrum at the Sun assuming a hydrogen column density of 10^{18} cm^{-2} in all directions between the Sun and this interface. The spectrum was dominated by bound-bound emission lines resulting in a local Γ_H ranging from 1.6×10^{-15} s^{-1} to 5.1×10^{-15} s^{-1} depending on the angle of the magnetic field with respect to the cloud's radial direction. Therefore this (as yet) unobserved radiation is comparable to, or a factor of 5 greater than, that produced by ϵ CMa (Table 2). Recent results using *EUVE* to measure diffuse radiation have been able to place 3 σ upper limits less than Slavin's predictions for the shorter wavelength emission lines (Jelinsky, Edelstein, & Vallerga 1994). However, better limits at the longer wavelengths must await further analysis because of the difficulty of removing the local 584 Å background radiation from the diffuse spectra. We will proceed in the following section assuming that ϵ CMa is the dominant source hydrogen ionization with the understanding

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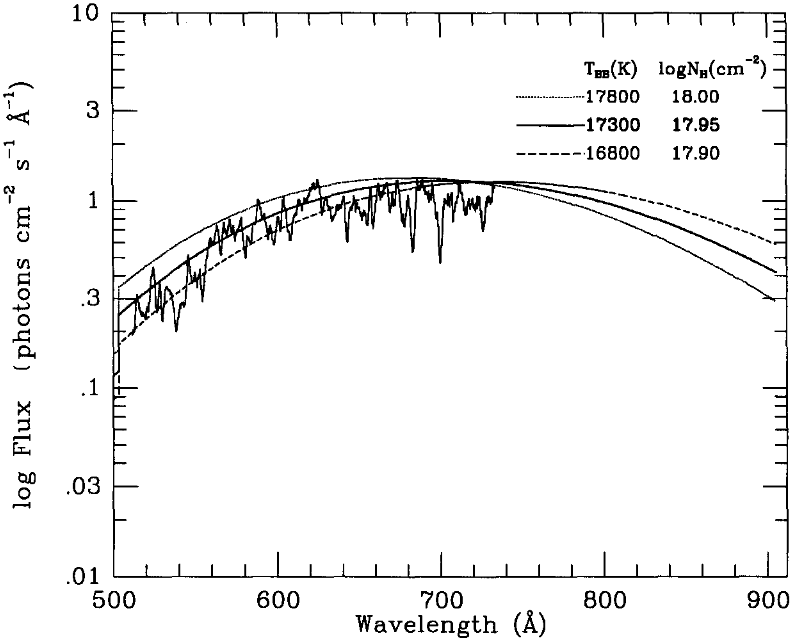

FIGURE 2. The same spectrum of ϵ CMa as in Fig. 1 but plotted logarithmically. The three lines overplotted represent simple blackbody curves attenuated by neutral hydrogen absorption. These models were used to extrapolate the ϵ CMa spectrum from 730 to 912 Å which could not be measured with *EUVE*. Solid line: $T = 17300$ K, $\log N_{\rm H^o} = 17.95$. Dotted line: $T = 17800$ K, $\log N_{\rm H^o} = 18.00$. Dashed line: $T = 17300$ K, $\log N_{\rm H^o} = 17.90$.

that a lower limit will result and hydrogen ionization fraction will increase if the diffuse emission from the conductive interface is eventually determined to be significant.

3. Ionization State of the Gas Near the Sun

The relevant equations describing ionization equilibrium and charge balance are given in Bruhweiler & Cheng 1988, and the choice of parameters required to determine Γ are fully explained in Vallerga & Welsh (1995). We assume that the temperature of the Local Cloud near the Sun is 7000 $\pm$ 1000 K. We base this assumption on recent high-resolution absorption measurements of interstellar Lyα observed toward the nearby stars of Cappella (Linsky et al. 1993) and Procyon (Linsky et al. 1994). This value is consistent with the slightly higher temperature of 8000 $\pm$ 1000 K derived by Bertaux et al. (1985) using hydrogen gas cell Lyα line widths of the local interstellar wind. At 7000 K, the hydrogen recombination rate, $\alpha(\rm H^o)$, is 3.4×10^{-13} cm^3 s^{-1} (Halpern & Grindlay 1980). The collisional ionization rates are insubstantial compared to the photoionization rates at this temperature (Lotz 1967).

If we assume a neutral hydrogen density of 0.065 cm^{-3} and a neutral helium density of 0.001 cm^{-3} from the solar backscatter measurements (Chassefiere et al. 1986), and that $n(\rm He^o) > n(\rm He^+) > n(\rm He^{++})$, then the photoionization parameter dominates the charge

TABLE 2. Electron density and hydrogen ionization fraction near the sun resulting from ϵ CMa

Assumed $n(\mathrm{H}^\circ)$ (cm^{-3})	$n_e(\mathrm{cm}^{-3})$	X_H†
.065 (Chassifiere et al. 1986)	.015	.19
.110 (Linsky et al. 1993)	.019	.15

† $X_\mathrm{H} \equiv n(\mathrm{H}^+)/[n(\mathrm{H}^+) + n(\mathrm{H}^\circ)]$

exchange terms in the ionization balance equations (Vallerga & Welsh 1995). By then equating n_e with $n(\mathrm{H}^+)$, assuming that helium is mostly neutral, results in the simplified formula:

$$n_e^2 \cong n(\mathrm{H}^+) \cdot n_e = \frac{\Gamma(\mathrm{H}^+) \cdot n(\mathrm{H}^\circ)}{\alpha(\mathrm{H}^\circ)}. \tag{3.2}$$

This equation shows the square root dependence of the electron density on the ionization rate and local neutral hydrogen density. Table 2 gives the electron densities and ionization fraction X_H ($\equiv n(\mathrm{H}^+)/[n(\mathrm{H}^+) + n(\mathrm{H}^\circ)]$) assuming the neutral density measured in the local interstellar wind as well as the higher density determined from average line-of-sight measurements to nearby stars. To check our assumption about the charge exchange rates and helium densities a posteriori, we can take our derived ionized hydrogen density together with the measured values of the neutral densities (Table 2) to determine the ionization fraction of helium. Using this technique, a helium ionization fraction, X_He, can be constrained to be between 0% and 33% assuming the two extremes of hydrogen density used in Table 2. In both density cases the charge exchange contribution to the hydrogen ionization balance is still less than 1% of the photoionization caused by ϵ CMa. We can compare this range of helium ionization fraction to the only directly measured ionization fraction of helium observed toward the hot white dwarf GD246 (Vennes et al. 1993). Using the *EUVE* derived spectrum, Vennes et al. were able to detect the interstellar He II edge at 228 Å as well as the autoionization feature of He I at 206 Å giving both the neutral and singly ionized column densities of helium. They derived a helium ionization fraction of 25%. However, it is not clear whether the high hydrogen column in this direction is an extension of the Local Cloud or a separate cloud nearer to the white dwarf (d = 65 pc). Note that the ion densities derived in Table 2 assume no helium ionization. If the ionization fraction of helium was as high as 33% then the electron density would increase by 25% with a corresponding decrease of $n(\mathrm{H}^+)$.

3.1. *Comparison with Previous Work*

The present empirical derivation of the ionization fraction of hydrogen from ϵ CMa alone gives a lower limit to the ionization state of the local hydrogen gas. Therefore, this result cannot rule out other sources of ionization (such as conductive boundary EUV flux or recent supernova shocks) that might explain the high ionization fraction implied by the ratios of neutral densities found inside the heliosphere. A compilation of neutral hydrogen and helium density measurements inside the heliosphere taken by various instruments gives typical densities $n(\mathrm{H}^\circ) \sim 0.05\ \mathrm{cm}^{-3}$ and $n(\mathrm{He}^\circ) \sim 0.01\ \mathrm{cm}^{-3}$ (Chassefiere et al. 1986). The fact that the ratio of these densities is not the canonical cosmic ratio of 10 implies that hydrogen must be partially ionized in the solar system with an ionization fraction X_H = 0.3–0.7 if helium is completely neutral and greater if helium is partially ionized.

Our derived electron densities can be compared to those determined by the Mg absorp-

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tion line ratio technique (Cox & Reynolds 1987). The local electron density is derived by measuring the interstellar column densities of Mg I and Mg II toward nearby stars and using the standard ionization equilibrium equations. This technique is fraught with uncertainties, not only in the measurement of the ratio since the Mg II lines are usually highly saturated, but also in the assumed ionization and recombination constants, Γ and α, because of uncertainties in the radiation field and temperature. Results for the derived local electron density range from 0.026 to 0.10 cm^{-3} averaged over the line of sight, though there are certain directions where this value is much smaller (Bruhweiler et al. 1984; Cox & Reynolds 1987). These densities equal or exceed those found from ϵ CMa alone, though they come from measurements of stars with distances 8, 20, and 40 pc whose lines of sight certainly sample the hot, ionized gas and the conductive interface with the Local Cloud.

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