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PHOTOIONIZATION OF GALACTIC HALO GAS BY OLD SUPERNOVA REMNANTS

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RESUMEN

Presentamos nuevos cálculos de la contribución del enfriamiento del gas caliente en remanentes de supernova (SNRs) viejos a la fotoionización del gas ionizado tibio en nuestra Galaxia. Mostramos que la emisión de SNRs que se enfrían es de radiación suave ($\bar{E} \sim 20$ eV), de manera que hay una alta eficiencia de conversión de la energía de la explosión en fotones ionizantes, ∼30 – 40%. Dada esta alta eficiencia, las SNRs pueden ser responsables de hasta un 50% de la medida de emisión observada en el medio ionizado tibio de nuestra Galaxia. Los flujos obtenidos son también consistentes con el fondo de rayos-X suaves a altas latitudes y las observaciones de rayos-X suaves en galaxias externas. Encontramos que nuestro modelo puede explicar la ionización de las nubes observadas en la dirección de la estrella del halo HD 93521, donde no hay estrellas O cercanas a la línea de visión.

ABSTRACT

We present new calculations on the contribution from cooling hot gas in old supernova remnants to the photoionization of warm ionized gas in the Galaxy. We show that the emission from the hot gas in cooling supernova remnants (SNRs) is soft ($\bar{E} \sim 20$ eV) and, as a result, the efficiency of conversion of supernova explosion energy into ionizing photons is high, ∼30 – 40%. Given this high efficiency, supernova remnants could be responsible for up to 50% of the emission measure observed for the warm ionized medium in the Galaxy. Our model flux is also consistent with the diffuse soft X-ray background at high latitude and with soft X-ray observations of external galaxies. We consider the ionization of the clouds observed towards the halo star HD 93521, for which there are no O stars close to the line of sight. We find that the observed ionization can be explained successfully by our model flux.

Key Words: **GALAXY: HALO — ISM: CLOUDS — ISM: GENERAL — SUPERNOVA REMNANTS — X-RAYS: ISM**

1. INTRODUCTION

The ionization of the warm ionized medium (WIM) remains problematic. Although it appears that O stars have sufficient power to maintain the WIM, their spatial distribution is very non-uniform in contrast to the relatively smooth Hα background. Most O stars are confined to OB associations and have a low scale height. The means of transporting the ionizing photons from the stars to the locations where the ionized gas is observed remains unexplained in some cases.

2. PHOTOIONIZATION BY SUPERNOVA REMNANTS

Supernovae are an important source of energy for the interstellar medium (ISM) and thus they could potentially be a significant source of ionization for the WIM. The estimated power per unit area of the Galactic disk required to maintain the Hα background is large $P_{\mathrm{H}\alpha} \approx 10^{-4}$ erg s^{-1} cm^{-2} (Reynolds 1990). The SN power, $P_{\mathrm{SN}} \equiv S_A E_{\mathrm{SN}}$ (where S_A is the SN rate/area of the disk and E_{SN} is the SN explosion energy) has been

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estimated to roughly equal $P_{\mathrm{H}\alpha}$ (Reynolds 1990). Using $S_A = 3.8 \times 10^{-5}$ kpc^{-2} yr^{-1} (McKee & Williams 1997) and $E_{\mathrm{SN}} = 10^{51}$ ergs yields $P_{\mathrm{SN}} = 1.3 \times 10^{-4}$ erg s^{-1} cm^{-2}.

To judge whether SNRs can be an important source of ionization for the WIM requires us to estimate the efficiency of conversion of explosion energy into photoionization. Central to the calculation of this efficiency is the spectrum of the emitted radiation. We parameterize this by

$$\phi_\nu = \frac{\int dt \int \epsilon_\nu dV}{E_{\mathrm{SN}}} \ , \tag{1}$$

where ϵ_ν is the emissivity in a supernova remnant as a function of position and time during its evolution and ϕ_ν is the fraction of SN power radiated per unit frequency interval.

Having determined ϕ_ν, we can get the number of ionizing photons per SN by $\mathcal{N}_\gamma = E_{\mathrm{SN}} \int_{\nu_H}^{\infty} \phi_\nu / h\nu \, d\nu$, where $h\nu_H$ is the ionization potential of hydrogen. Because most of the radiation is soft nearly all the ionizing photons produced will be absorbed in the Galactic disk.

We can compare $\mathcal{N}_\gamma$ to the theoretical maximum number of ionizing photons per SN to give an overall efficiency factor:

$$\xi = \frac{\mathcal{N}_\gamma}{(E_{\mathrm{SN}}/h\nu_H)} = \frac{h\nu_H \, \phi(> \nu_H)}{\bar{E}}, \tag{2}$$

where $\phi(> \nu_H) = \int_{\nu_H}^{\infty} \phi_\nu d\nu$, and $\bar{E}$ is the mean energy of an ionizing photon.

3. METHODS AND RESULTS

Our method is as follows. Using a 1D numerical hydro code (PPM Lagrangian remap method) we evolve a SNR in a homogeneous medium following the temperature, density and non-equilibrium ionization with time. We then use the Raymond & Smith (1977 + updates) code to calculate the spectra and integrate over volume and time to derive ϕ_ν. We did runs for ambient densities $n_a = 0.04$ – 1.0 cm^{-3} and with thermal conduction turned on and off. Our results include:

- SNRs are relatively efficient at converting explosion energy into ionizing photons: $\xi = 0.31$ – 0.43 for the cases we calculated,
- $\bar{E}$ is low: 19.5 – 21.4 eV,
- SNRs can account for an ionization rate of 1.8 – 2.5×10^6 s^{-1} cm^{-2} or an emission measure (half disk $\perp$ to the plane) of 0.92 – 1.3 cm^{-6} pc.

Comparing our results for the ionizing spectrum we find that hot gas emission can produce $\lesssim 50\%$ of the observed ("typical") emission measure perpendicular to the Galactic plane as derived from Hα measurements. We cannot make any direct comparisons of the ionizing spectrum with observations because of the short mean free path of EUV photons in the ISM and the lack of any direct detection of the local background as of yet. We can, however, compare with the next higher energy portion of the spectrum, the soft x-rays. Doing this we find that our calculated spectrum is consistent with the observed soft x-ray diffuse background in the Wisconsin *B* and *C* bands at high Galactic latitudes where we get substantial contributions from distant regions. In addition, we calculate the amount of soft x-ray flux one would observe by viewing the Galaxy from the outside and find that our model flux is consistent with soft x-ray emission observed by *ROSAT* from face-on spirals. If a substantially larger fraction of the x-rays escaped rather than being absorbed within the Galaxy, face-on spirals would appear brighter in soft x-rays than they do.

4. THE EXAMPLE OF HD 93521

The line of sight towards HD 93521, a high latitude O star ($\ell = 183°$, $b = 62°$, $D \approx 1700$ pc) is a nearly ideal test of the SNR ionization model. UV (*HST*) observations (Spitzer & Fitzpatrick 1993) reveal 9 velocity resolved features ("clouds") all apparently warm, low density ($n \sim 0.3$ cm^{-3}), partially ionized regions and very little cold gas along the line of sight. There are no O stars (other than HD 93521 itself) close to the line of sight. Even allowing for ionization out of the Galactic plane (Strömgren cones) does not result in ionization by O stars along this line of sight (Miller & Cox 1993).

The absorption line data shows 2 sets of features, "fast" ($v_{\rm LSR} \sim -50$ km s^{-1}) and "slow" ($v_{\rm LSR} \sim 0$ km s^{-1}) clouds. At each of the velocities, lines of several different ions have been identified. Of particular importance for us are the C II*, S II, and S III ions. H I 21 cm emission data can be split into the velocity components of the UV lines leading to reasonable gas phase abundances.

Recently, optical emission lines have also been observed towards HD 93521 in diffuse emission observed with WHAM (see Haffner, Reynolds this volume). The emission line data is at lower velocity resolution (and much lower spatial resolution). As a result the emission lines can only be split into the fast and slow groups, and cannot be resolved into individual cloud features. To date, Hα, [N II] λ6584, and [S II] λ6716 have been observed.

To calculate the ionization in clouds due to the SNR emission, we generated a mean intensity by assuming randomly distributed clouds with column density N(H I) $= 1.5 \times 10^{19}$ cm^{-2} (typical of HD 93521 l.o.s.). The low Hα intensity indicates that the SNR emission is more than sufficient to create the emission measure towards HD 93521. We scale the intensity by 0.68 to match the observed Hα. To carry out the calculation of the ionization we use the photoionization equilibrium code CLOUDY (Ferland 1996). We fix the temperature at either 6000, 8000 or 9000 K, and explore a range of thermal pressures, $P/k = 1000 - 2 \times 10^4$ cm^{-3}K.

Fixing our model to match the Hα and the S II absorption line observations, we find we can match observed C II*/S II and S III/S II ratios. High thermal pressures ($P/k = 10^4 - 2 \times 10^4$ cm^{-3}K) are required to match the slow clouds. [S II] λ6716 and [N II] λ6584 emission line strengths are more problematic requiring that the ionized regions of the clouds be substantially warmer than the neutral regions.

5. CONCLUSIONS

We have carried out calculations of the efficiency of converting supernova explosion energy into ionizing photons. The high efficiencies we have found ($\sim$30 – 40%) and the insensitivity to model parameters convinces us that supernova remnants must provide a substantial fraction of the ionizing photons that create the warm ionized medium in the Galaxy. For the test case of the line of sight towards HD 93521, we find we can reproduce the ionization observed, though some aspects of the clouds along this line of sight remain problematic.

The work described in this paper has been carried out in collaboration with Chris McKee and Dave Hollenbach who are co-authors on a paper giving a fuller description of our results (Slavin, McKee, & Hollenbach 2000, in preparation).

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