ON THE IONIZING SOURCES IN SPIRAL GALAXIES: I. FROM CENTRAL REGIONS TO THICK DISK AND DISK-HALO CONNECTION

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1. INTRODUCTION

The problem of the ionization in the spiral galaxies, including our own, the Milky Way is not solved at the moment (for survey see e.g. [1]) although there are some indications that could lead towards solution [2, 3, 4].

We assume the Sofue’s model of the rotation curves of spiral galaxies [5] based upon the observation of CO line emission and combined with HI and optical observations. This model has four mass components: nuclear mass component, a central bulge, a disk, and a massive halo. One can add the fifth component for the Milky Way [5] at the nucleus e.g. [6,7]. As a characteristic of the ionization we study the number density of free electrons in the interstellar medium throughout the Galaxy, \( n_e \), using the Taylor and Cordes model (TC93) [8] as well as its updated version (LC98) [9].

2. THE CASE OF THE MILKY WAY

We examine our Galaxy – Milky Way, in many respects a typical spiral galaxy, in more detail. In the textbooks one usually encounters the fact that in the disk of a spiral there are H II regions that are ionized by the radiation from young and massive stars, associations of OB stars [10]. Although the average properties of the ionized gas are rather well known the source of this ionization is still the subject of the discussion of the astronomers, astrophysicists, and even cosmologists. Following Sciama [1] one can state the following important problems.

- The scale height (defined as the column density on one side of the galactic plane divided by the volume density in the plane) of free electron component of the interstellar matter (ISM) is \( h_e = \left( \frac{N}{\langle n_e \rangle_0} \right) \approx 668 \) pc, where \( N \) is the the total column density \( (N \sim 6.8 \times 10^{19} \) cm\(^{-2} \)) and \( \langle n_e \rangle_0 = 0.033 \) cm\(^{-3} \) is the mean electron density at the midplane. However, the sources such as O stars or supernovae have a much smaller scale height \( (h_e \sim 100 \) pc).
- As pointed out by Reynolds [12] the nature and origin of the ionized gas about the galactic disk is not well understood. The power that is required to maintain the diffuse, ionized gas ranges from minimum of \( 5.3 \times 10^{-5} \) ergs s\(^{-1} \) cm\(^{-2} \) (if all the gas has \( T \sim 10^4 \) K) to \( 6.6 \times 10^{-3} \) ergs s\(^{-1} \) cm\(^{-2} \) (\( T \sim 10^5 \) K). As stressed by [1] among all known sources of power only Lyc (Lyman continuum) photons from O stars and energy from supernovae have or exceed the required power.
Therefore, since the interstellar medium is highly opaque to hydrogen-ionizing radiation, the following question remains: how can this radiation travel hundreds of parsecs from the parent O stars in order to produce the diffuse ionized gas? (e.g. [13]). Careful study of the interstellar hydrogen towards different pulsars suggests that column densities of free electrons along two line segments cannot be accounted for by H II regions around B stars or hot white dwarf stars. Reynolds [12] gives three possibilities for the explanation of the existence of the ionized gas: (i) morphology for the interstellar H I is very different from that usually depicted, (ii) Lyc luminosities for early B or hot white dwarf stars are more than an order of magnitude larger that the currently accepted values and (iii) there exists an additional, yet unrecognized source of ionization within the Galactic disk.

The mean electron density in opaque intercloud regions within a few hundred parsecs of the Sun as function of a Galactocentric radius is approximately constant [8]. TC93 modeled the electron density of a certain Galactic location as the following sum (the fifth component was added in LC98):

$$n_e(x, y, z) = n_{1}g_{1}(r)\text{sech}^2(z/h_1) + n_{2}g_{2}(r)\text{sech}^2(z/h_2) + \sum_{i=1}^{4}f_{i}g_{a}(r, s_{j}) + n_{GC}g_{GC}(u) + n_{GC}g_{GC}(r)h_{GC}(z)$$ (1)

The detailed description of each component is given in TC93 and LC98 and because of space limitation we just give few remarks: $r$ is the Galactocentric distance projected onto the plane and is equal $r = (x^2 + y^2)^{1/2}$, the sum goes over four spiral arms, $n_{i}$ , $i = 1...5$ denotes the density in different regions, $f_{i}$ , $i = 1...4$ are scale factors, $g_{i}$ , $i = 1...5$ are functions of position, $h_{i}$ , $i = 1...4$ are scale heights and $z$ is the height above the galactic plane. Electron densities as a function of $R$ are presented in TC93 (in their Fig. 3).

The fifth component becomes dominant up to a Galactocentric distance of 0.6 kpc. In this area, numerous point sources of ionization are responsible for the total Galactic center (GC) component contribution, especially within the nuclear bulge ($r \leq 250$ pc).

At a dynamical center of the Galaxy, SgrA* – a nonthermal synchrotron radio-source coinciding with the estimated $2.6 \times 10^{6}M_{\odot}$ black hole [6], lies surrounded with thermal plasma – SgrA West, ionized by a cluster of few tens of young, hot ($T_{\text{eff}} = 3.5 \times 10^{4}$ K), luminous O stars within a central ($r = 1$ pc) cavity [14]. SgrA West consists of a mini-spiral and an extended component with $n^{\text{sp}}_e \sim 10^{4}$ cm$^{-3}$ and $n^{\text{ext}}_e \sim 10^{3}$ cm$^{-3}$ [15]. Some local features of ionized gas such as the Bullet (4” northwest of SgrA*) [16] and the Sickle [17] contribute to the total electron density near GC with $3 \times 10^{4}$ cm$^{-3}$ and 150 cm$^{-3}$ respectively.

At a distance of 30 pc behind the GC, lays SgrA East – the probable supernova remnant colliding with a molecular cloud at 200 pc from GC, contributing with $n_e = 6$ cm$^{-3}$ electron density. It could be heated by O stars formed as a result of collision [19].

Another large ionized area near GC is a Sgr B2 – the largest luminous H II/molecular cloud region at 100 pc from GC surrounding the circumnuclear disc (2-12 pc from GC) in which the SgrA West is embedded. SgrB2 could be interpreted as an extended accretion disk around a central dormant black hole [20].

If we now wish to study the ionization in outer parts of the Galaxy we will encounter the lack of star forming regions in the outskirts of spiral galaxies [21]. From the radio observations (21 cm) it was noticed that HI disks in at least two galaxies (M33 and NGC3198)
have sharp edges [1]. HI column density drops from few times $10^{19}$ cm$^{-2}$ to few times $10^{18}$ cm$^{-2}$ within 1 to 2 kpc. When the incident photon flux $F$ is monochromatic and the ionized gas is smoothly distributed (with density $n$ and thickness $b$) the edge will occur when $N \sim \frac{F}{\alpha n}$, where $\alpha$ is the recombination coefficient. If one wishes to estimate the intergalactic hydrogen-ionizing flux $F$, one can measure H$\alpha$ surface brightness of clouds opaque to $F$ exposed to this flux – each hydrogen recombination produces 0.46 H$\alpha$ photons on average (e.g. [1]). After extensive studies an upper limit for ionizing flux is currently thought to be: $F_{\text{ext}} \leq 6 \times 10^5$ cm$^{-2}$ s$^{-1}$ [1]. One can generally estimate $F$ by measuring the recombination emission induced by it [22, 23]. Although uncertainties connected with this quantity are large, their relevance is largely beyond the scope of this paper, since metagalactic flux is the dominant ionization source only at large heights above the plane of the disk and at large galactocentric radii, i.e. in the halo gas. We briefly mention that an interesting candidate for ionizing source present in all galaxies could be the massive decaying neutrino, which not only solves the problem of the ionization, but also accounts for the dark mass present in every spiral galaxy. There exist a large number of alternative sources of intergalactic ionization: population III stars, elliptical galaxies, dwarf galaxies, starbursts, quasars concealed by dust obscuration in intervening galaxies, reflection-dominated hard x-ray sources, accreting black holes and supernova-driven winds from early galaxies ([1], and references therein), or non-radiative sources like large-scale intergalactic shocks. Most of them, fortunately, are not operational in late epochs of galactic evolution, and their respective influences will be considered in the extension of the present work.

The significance of these results lies mainly in exciting possibility of direct testing of models through high-sensitivity observations of recombination lines [24]. One of problems facing any such observations, especially in cases of small inclination angles, is strong signal originating in the fluorescing haloes interfering with light from the disk. We roughly compare two intensities using the estimate of local ($z = 0$) intensity of H$\alpha$ halo emission from [23], and form:

$$I_{\text{disk}} \approx 42.9 I (N_{\text{HI}})^{-1} T^{0.73},$$  

where $I$ is the value of the numerically solved integral $\int n_e^2 ds = 2.75 T_0^{0.9} I_\alpha$ cm$^{-6}$ pc [26] and expression for $n_e$ is taken from the rhs of the eq. (1) using first two terms. $N_{\text{HI}}$ is the neutral hydrogen column density along the line of sight through the halo only. In the Figure 1. we plot the dependence of $I_\alpha$, that is interstellar H$\alpha$ intensity in rayleighs (1 R=10$^6$/4$\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$), on the Galactocentric distance, $r$. Although poorly known, $N_{\text{HI}}$ is expected to be $\sim 10^{16}$ cm$^{-2}$, characteristic of the average Ly$\alpha$ absorption originating in haloes of normal galaxies at low redshift [25]. Therefore, the signal from the disk should be strong enough to be analyzed in most of the typical cases. Of course, the kinematic properties of the emission lines originating in halo and disk will also be different, helping practical discrimination between the two.

We note that Reynolds et al. [27] obtain for $I_\alpha$ at $|z| \approx 1$ kpc the following value: $4\pi J \approx 2 \times 10^6$ photons cm$^{-2}$ s$^{-1}$, where $J$ is the incident Lyman continuum flux, that can be compared with our estimate depicted in the Figure 1. The project that is currently operating – Wisconsin H$\alpha$ Mapper (WHAM) [28] will provide the data on the diffuse ionized hydrogen through the optical H$\alpha$ line. In a subsequent work, we intend to include
all terms in the eq. (1), in order to get complete picture of expected Hα emission, by solving the integral \( \int n_e^2 ds \).

**ACKNOWLEDGEMENT:** We acknowledge the help of Prof. James Cordes in obtaining the code written for the paper TC93.

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Figure 1. The interstellar H$\alpha$ intensity $I_\alpha$ in rayleighs is plotted against the Galactocentric distance $r$ in kiloparsecs. Different values for the height above the Galactic plane, $z$ (where $z$ goes from the disk to 1 kpc) are taken into account.