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The Interstellar Halo of Spiral Galaxies: NGC 891

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Introduction.

It is now being increasingly recognized that the warm, ionized medium (WIM) is a major phase of the interstellar medium in our Galaxy. At the Solar circle, this medium has a mean density ~ 0.03 cm^{-3} and a temperature of ~ 7500 K. This gas is detected by two principal techniques: dispersion of pulsar signals and faint, diffuse optical line emission due to recombination (Hα) and collisional excitation of metastable lines ([S II] and [N II]). The power needed in the form of ionizing photons to match the observed recombinations exceeds the power injected by SNe. Consequently it is thought that the WIM is ionized by stars: young stars, hot white dwarfs, planetary nebulae etc. The unknown topology of the neutral ISM has so far prevented us from precisely identifying the dominant ionizing agents.

The vertical structure of the WIM is of considerable interest from many viewpoints. In our Galaxy, pulsar dispersion measure data appear to indicate that the local WIM layer is about 3 kpc thick (two-sided) and a filling factor, ϕ, somewhere between 10% and 30%. However, some WIM exists at $|z| > 3$ kpc as evidenced by UV absorption studies towards hot halo stars, stars in the Magellanic Clouds and nuclei of active galaxies.

The large scale distribution of the WIM phase can provide a crucial handle on our understanding of the WIM. For example, the radial variation of the WIM phase can throw considerable light on the nature of the ionizing sources. Knowledge of the vertical distribution of the WIM is certainly needed before issues of pressure support and ionization can be addressed. Unfortunately, our location prevents us from obtaining a comprehensive view of the large scale structure of the Galactic WIM. Consequently, we started a program of narrow band imaging in the Hα line of nearby galaxies. NGC 891, an edge-on Sb galaxy and considered to be similar to our Galaxy, was our prime target.

Observations and Reduction

The observations were done at the 60-inch telescope of the Palomar Observatory. A reimaging camera followed by a CCD detector (TI 800^2) enabled us to obtain a wide field, 16 arcmin$\times$ 16 arcmin. NGC 891 was observed with an Hα filter of 15 Å bandwidth and a much wider continuum filter.

All cameras, especially reimaging cameras, suffer from scattered light problem viz. light from a bright source is scattered over a large portion of the detector. For most normal imaging projects, this can be ignored. However, in our case, the expected WIM emission from NGC 891 is weak and light scattered from the bright HII regions which are confined to the disk of the galaxy could mimic diffuse emission at high $|z|$. Let $\epsilon(x)$ be the scattered PSF. Then the observed image, $B(x)$ is

$$B(x) = A(x) * [1 + \epsilon(x)]$$

where $A(x)$ is the image that one would have obtained in the absence of scattering. We observed a bright star and measured $\epsilon(x)$. (In reality, $\epsilon(x)$ is a function of the position of the centroid of the bright star; we ignore this subtle but numerically unimportant correction in the analysis reported here). It is easy to show that to $O(\epsilon(x)^2)$, we can get a scatter corrected image:

$$
\begin{aligned}
A_{cor}(x) &= B(x) - B(x) * \epsilon(x) \\
&= A(x) - [A(x) * \epsilon(x)] * \epsilon(x). \\
&\simeq A(x)
\end{aligned}
$$

The on- and off-band images after the above deconvolution were registered, gain corrected by using a grid of stars and subtracted to yield a continuum subtracted Hα image. In a similar manner, images were obtained in the $\lambda\lambda$ 6713Å and 6731Å line of [S II]. Here we present only the Hα observations.

Assuming a distance of 9.5 Mpc to NGC 891 (equivalent to assuming a Hubble's constant of 50 km s^{-1} Mpc^{-1}), our pixel of 1.2 arcsec translates to 57 pc. This resolution is more than sufficient to study the diffuse ionized gas in NGC 891. Indeed we purposely degrade the spatial resolution in one axis to further improve the sensitivity e.g. in order to study the z-distribution we divide the galaxy into five regions: the bulge, the mid-section (East and West) and the outer galaxy (East and West). The final reliable sensitivity achieved in such 1-dimensional slices is an emission measure limit of $EM \sim 0.3$ cm^{-6} pc where we have assumed an temperature of 10^4 K to convert the observed Hα emission to EM.

Distribution of the Diffuse Ionized Gas

Our preliminary results show that NGC 891, a spiral galaxy considered to be rather similar to our Galaxy, has more WIM than our Galaxy. We readily detect strong integrated emission from the HII regions confined to the plane of the galaxy. Diffuse emission is easily detected out to a radial distance of 11 kpc and to $|z| \simeq 5$ kpc. The latter detection is perhaps the most significant result of our project.

Mid-Region ($3 < R < 6$ kpc). At our sensitivity limit, the gas is readily detected to $|z| \simeq 5$ kpc. Averaging the gas between galactocentric radius 2 and 5 kpc, the emission measure can be represented as

$$EM(z) = 75\ e^{-|z|/2.2\ \mathrm{kpc}}\ \mathrm{pc\ cm^{-6}}.$$

The above one-component fit clearly falls short of the observations for high $|z|$. A second component with a scale height larger than 2.2 kpc is needed to describe the very high $|z|$ emission. Since $EM(z) = \langle n_e^2 \phi \rangle(z) P$ where P is the effective path length and $\phi(z)$ is the filling factor of thermal electrons we deduce that the vertical density distribution of the electrons is given by

$$\langle n_e \phi \rangle(z) = 0.1\sqrt{\phi(z)}\ e^{-|z|/4.4\ \mathrm{kpc}}\ \mathrm{cm^{-3}}.$$

In arriving at the above equation we have used an effective path length $P = \sqrt{R_g^2 - R_0^2}$ where $R_0 = 3.5$ kpc, the mean galactocentric radius of the slice and R_g is the effective radius of the diffuse gas, assumed to be 12 kpc.

Assuming a $\phi \sim 0.25$ (the value appropriate for the Solar neighbourhood as estimated by Reynolds) we derive a mean density of 0.05 cm^{-3} which is about twice the mean density at the Solar circle.

The vertical column density of the electrons is given by $\int_{-\infty}^{+\infty} \langle n_e(z) \rangle dz$ which turns out to be $420\sqrt{\phi/0.2}$ cm^{-3} pc, considerbly larger than the equivalent value of 70 to 100 cm^{-3} pc at the Solar circle of our Galaxy. While there is evidence that the WIM increases in the inner region of our Galaxy by a factor of perhaps 2 there is no doubt that the WIM layer in NGC891 is more massive than that in our Galaxy.

Outer Galaxy ($5 < R < 9$ kpc). We detect Hα emission out to $|z| \simeq 5$ kpc. A one component fit to a slice averaged over galactocentric radius 5 and 9 kpc yields

$$EM(z) = 45\ e^{-|z|/2.4\ \mathrm{kpc}}\ \mathrm{pc\ cm^{-6}}.$$

As before, this model falls below the observed emission for large $|z|$. The surface density of the thermal electrons can be estimated as before and is found to be $376\sqrt{\phi/0.2}$ cm^{-3} pc or 11 $M_\odot$ pc^{-2} (this includes correction from He). In contrast, the HI surface density in NGC 891 is 6 $M_\odot$ pc^{-2}. These observations show the importance of the WIM in spiral galaxies like NGC891.

Beyond galactocentric radius of 9 kpc, it becomes quite increasingly hard to see the high-$|z|$ emission. Between 9 and 12 kpc, we detect emission quite easily to a z-height of 1.4 kpc. Study of the WIM in this region is important because ionization by young stars probably comparable to other sources such as the extragalactic UV background.

Inner Galaxy ($0 < R < 3$ kpc. NGC 891, like our Galaxy, has a central hole in both HI and CO. Coincident with the inner edge of the molecular distribution (at $R = 3$ kpc) there is an enhanced WIM emission. We are in the process of inferring the bulge ($R < 3$ kpc) contribution from our data. Pending this we advise you to ignore any previous draft of this work that you may have seen.

Summary

We have detected the Warm Ionized Medium (WIM) phase in the galaxy NGC 891. We find that the radial distribution of the WIM follows the molecular or young star distribution – an expected dependence. The amount of the WIM in this galaxy exceeds that in our Galaxy. The major surprize is the large thickness of the WIM phase – about 9 kpc instead 3 kpc as in our Galaxy. Clearly, this is the most significant result of our observations.

The presence of low ionization gas at high $|z|$ as well as at large galactocentric radii (where young stars are rare) is an important clue to the origin of the halo and observations such as the one reported here provide important data on this crucial question. In particular, the ionization of gas at high $|z|$ imply that either the UV photons manage to escape from the disk of the galaxy or that the extragalactic UV background plays an important role.

Bulk of the WIM in spiral galaxies is a result of star-formation activity and thus our results can be understood by invoking a high star formation rate in NGC891. Only the concerted action of supernovae can get the gas to the large z-heights as is observed in this galaxy. Support for this view comes from our detection of many "worms" i.e. bits and pieces of supershells in the form of kilo-parsec long vertical filaments. We also see a 600-pc size supershell located nearly one kpc above the plane of the galaxy.