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Conference Highlights

Green Bank Workshop on Warm Ionized Gas in Galaxies[1]

"Warm Ionized Gas in Galaxies" was a Green Bank Workshop held 1999 September 23–25 at the National Radio Astronomy Observatory in Green Bank, West Virginia. The workshop brought together ~40 scientists from around the world who study warm ionized gas—primarily the warm ionized medium (WIM) in our Galaxy (also known as the Reynolds' layer) and diffuse ionized gas (DIG) in other galaxies.[2] The WIM is a major component of the Galactic interstellar medium and is clearly important in other galaxies as well. Because several groups are conducting new Galactic surveys of this material, there is a wealth of new extragalactic data, and there have been advances in theoretical and computational models in the past few years, a workshop on the warm ionized gas was timely. The workshop provided a forum in which our current understanding of the WIM could be reevaluated and important future observations could be outlined.

A total of 31 invited and contributed presentations were given. In the tradition of past Green Bank Workshops, emphasis was placed on open discussions. Below we summarize some of the results presented, conclusions drawn in the discussions and future observations that seem particularly desirable.

Hα *surveys.*—During the course of this workshop several new surveys of the Hα emission from the WIM in our Galaxy were presented. The Wisconsin Hα Mapper (WHAM) survey[3] has mapped the sky in Hα above $\delta \geq -30°$ with a 1° beam sampled every 1° with ~12 km s^{-1} spectral resolution using a Fabry-Pérot spectrometer. Selected regions have also been observed in He I λ5876, [O I] λ6300, [O III] λ5007, [N II] λ6583, and [S II] λ6716. The WHAM survey has produced the first (preliminary) direct measurement of the temperature of the WIM using the [N II] λ5755/[N II] λ6583 line ratio—suggesting temperature variations from ~5000 to ~15,000 K along a single line of sight.

The Virginia Tech Spectral Line Sky Survey[4] is mapping the sky at $\delta \geq -30°$ with arcminute resolution in ~10° wide fields using filters for the Hα recombination line and the [SII] $\lambda\lambda$6717, 6731 doublet emission lines. The Hα Sky Survey at CTIO in Chile[5] is mapping the sky at $\delta \leq -10°$ with arcminute resolution in ~10° wide fields of view using filters for the Hα recombination line.

These surveys have found that there is no line of sight that does not have Galactic Hα emission; that the Hα emission is quite filamentary on small angular scales; that ionization sources such as neutrino decay, cosmic-ray, and X-ray ionization can be excluded as major contributors to the ionization of the WIM; and that supplemental heating, in addition to the ionizational heating of the WIM, is required to explain the observed forbidden line strengths of [N II] λ6583 and [S II] λ6716.

Radio observations.—This topic was devoted to radio observations of the WIM. Interstellar turbulence can provide information on the distribution of electrons in the WIM from size scales of hundreds of kilometers up to astronomical units or perhaps parsecs. This information is obtained through radioastronomical observations of pulsar scintillations, flux variations of compact sources, and the angular broadening of compact sources. It may be possible for these observations to constrain the extent of the WIM in the radial direction in our Galaxy. Questions that remain to be answered are: Is the source of interstellar scintillation distributed uniformly throughout the WIM or in a few turbulent screens along the line of sight—possibly associated with the filaments seen in Hα? Are the turbulence and the MHD waves damped to provide an additional heat source to the WIM? Where do extreme scattering events fit into our understanding of the interstellar medium (ISM)?

Also underway are efforts to use the dispersion measures of pulsars combined with other information on the distribution of the WIM to update the "Taylor and Cordes" model for the Galactic distribution of electrons.

The WIM and other components of the ISM.—The connection between the WIM and other components of the ISM in our Galaxy was discussed. Several examples of the bubbles and superbubbles were presented in which "half" of a bubble shows up in H I and the other half in Hα

[1] Conference was organized and hosted by the National Radio Astronomy Observatory and was held in Green Bank, West Virginia, on 1999 September 23–25. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement with Associated Universities, Inc.

[2] The are many names for this phase of the interstellar medium: WIM, DIG, extended low density warm ionized medium (ELDWIM), etc. We will only use WIM throughout this report.

[3] http://www.astro.wisc.edu/wham/.

[4] http://www.phys.vt.edu/~halpha/.

[5] http://www.astronomy.swarthmore.edu/.

emission or X-rays. One example of this is the Orion-Eridanus bubble. Also, it was shown during the meeting how radio, infrared, and optical observations could be combined to produce rough estimates of the temperature in the WIM. In general it was agreed that our understanding of the relationship between the WIM and other components of the ISM is very limited. However, the current Hα surveys combined with observations at other wavelengths such as the infrared, UV, and X-rays should provide some answers within the next few years.

The WIM in other galaxies.—During the course of the workshop it became clear that the WIM in our Galaxy is the same component of the ISM as the DIG in other galaxies. A general understanding that the WIM covers most of the disk of galaxies with enhancements toward spirals arms and star-forming regions was also obtained. Evidence was presented that suggests that the star formation rate of a galaxy is related to the "strength" of the WIM. A general trend in edge-on galaxies is that the extraplanar emission from the WIM is brighter and more extended when the star formation rate per unit area is greater. There is also an association of extraplanar vertical filaments with ongoing star formation regions in the disks of edge-on galaxies. However, it was not clear if there is a universal smooth, underlying WIM that is not well correlated with the star formation rate in most galaxies. In other galaxies there was clear evidence presented that the WIM is brighter in spiral arms and near OB associations, but it is unclear if this is the same medium that is seen between spiral arms in other galaxies and near the Sun in our Galaxy.

Supplemental heating or ionization of the WIM.—A general consensus was that extra heating and perhaps ionization mechanisms beyond photoionization are required for the WIM in our Galaxy and in other galaxies. This extra heating may arise from such sources as dust grain heating from polycyclic aromatic hydrocarbons (PAHs), turbulent energy dissipation, MHD wave damping, cosmic-ray interactions, or magnetic field reconnection just to name a few. It was not obvious what observational tests could distinguish between the different heating mechanisms. Important questions are: Does the measured [O III] λ5007 emission require an additional ionization source, or does supplemental heating explain it all? Given supplemental heating, what role do variations in the ionization parameter now play in photoionization models and the interpretation of optical emission-line ratios?

Abundances and dust.—The abundances of elements in the WIM and the amount and type of dust in the WIM are not well determined. Observations of dust in other galaxies were presented; however, it still remains unclear how this dust is related to the WIM other than foreground obscuration. Important questions are: How well can the [N II]/[S II] ratios be used as an abundance indicator in the WIM of galaxies? Why is there a difference in the [N II]/[S II] ratio between the WIM (where it is lower) and the brighter H II regions in M31? What is the role of dust in absorbing and scattering the optical emission lines?

Theoretical issues.—Many of the theoretical discussions at this workshop focused on the nature of the sources of heating and ionization of the WIM. There was general agreement that O stars are the major source of ionizing photons. However, we are still struggling to find the correct models for the radiative transport of ionizing photons from OB associations to the diffuse ISM. For a mean column density from the midplane through the Galactic disk, $N_{\rm HI} \approx 3 \times 10^{20}$ cm^{-2}, ionizing radiation should be strongly attenuated after $\sim$100 pc. However, the topology of the ISM may be particularly relevant here. Large fluctuations in density and the existence of multiple phases (clouds, shells, intercloud medium, hot cavities) allow much larger penetration depths. Current theoretical models of escaping Lyman continuum (LyC) radiation find values of $\langle f_{\rm esc} \rangle \approx$ 5%–10% to distances $z > 1$ kpc, by including the dynamic role of superbubbles and a cloudy ISM.

The escape of LyC from starburst galaxies may also be significant for understanding the epoch of reionization of the intergalactic medium at redshifts $z > 1$. The uncertainties of these distant processes give increased relevance to the goal of understanding these processes in local counterparts such as the diffuse WIM in the Milky Way and in local spirals. A specific example is the detection of Hα emission from high-latitude high-velocity clouds, which can be used to probe the source and intensity falloff of LyC radiation above the Galactic disk.

Another open question is whether supershells and H II regions are leaky to LyC as a result of instabilities or fragmentation. New models of radiative transfer, both Monte Carlo and semianalytic, are now providing a detailed picture of the transport of lines and ionizing continuum radiation. A theoretical problem related to LyC transport and reprocessing is how to explain the low ratios, $Q_1/Q_0 \leq$ 0.03, of He I ionizing continuum to H I continuum, inferred from He I and H I recombination lines. These low values suggest a "soft" ionizing spectrum characteristic of late O stars or early B stars, but such sources may be insufficient to explain the absolute intensity of Hα emission. Observations of [O II] and [O III] emission lines could provide important additional constraints on models of ionizing sources and radiative transport.

The suggested extra heating sources of the WIM, in excess of the expected photoelectric heating of H and He, include cosmic rays, UV photoelectric heating of small dust grains and PAHs, cascade dissipation of turbulence, and ion-neutral collisional damping of MHD waves produced by the interactions of low Mach number shock waves and clouds. The workshop generated considerable debate on the trends of the heating rate and nebular temperatures (from [SII]/[NII] ratios) with galactocentric distance and scale height above the disk. We discussed the possible role of gradients in abundance and metallicity in a dynamically active ISM. Current observations suggest that the stellar abundance gradients of N and S are insufficient to explain the inference from line ratios that the diffuse WIM is hotter than classical H II regions. Theoretical models of the Local Cloud and Local Bubble are providing new insights into the role of EUV/soft X-ray photoelectric heating, as well as thermal conductive interfaces, in explaining the observed high ratios of H I/He I ≈ 14. However, the inferred gas pressures, $P/k \approx 6000$ cm^{-3} K, for the Local Cloud seem low compared with those for the hot Local Bubble.

Other new tools, observations and techniques.—The workshop was also a good forum for presenting possible new tools, observations, and techniques. Examples include (1) UV absorption-line data and how they may be combined with emission-line observations; (2) observation of hydrogen recombination lines in the IR; (3) the need to add new emission lines to the investigations—especially [O II] $\lambda\lambda$3727–3729, the most important cooling line in the WIM, which is unfortunately located in an inconvenient part of the spectrum; and (4) mapping halo velocity fields and rotation curves of galaxies using their WIM—allowing the rotation curves to be measured out of the plane of the galaxies for the first time with potential ramifications for constraining the hydrodynamic nature of the gas as well as the three-dimensional distribution of matter in galaxies.

The Green Bank Telescope (GBT) can help advance our knowledge of the WIM by mapping the Galaxy at low frequencies to determine the free-free absorption from the WIM of the Galactic background. This would provide information on the temperature of the WIM and its distribution. Also pointed out was the strong need for renewed searches for pulsars in globular clusters—particularly distant globular clusters with UV bright sources. This would provide invaluable probes of the WIM, since the distances to the globular clusters can be well established and are generally beyond the "extent" of the WIM along their lines of sight.

The workshop attendees were also treated to a sneak preview of a preliminary spectrum from the recently launched *FUSE* satellite and a closeup tour of the "soon to be launched" GBT.

We would like to thank all the participants of the "Warm Ionized Gas in Galaxies" Green Bank Workshop for many stimulating discussions that made this workshop a great success. We are also greatly indebted to the support staff at NRAO, Green Bank, for their efforts in making this an enjoyable conference.

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