H II Regions and the Warm Ionized Medium

A White Paper for the Astro2020 Decadal Review

Primary Area: *Star and Planet Formation*

Secondary Area: *Galaxy Evolution*

Loren D. Anderson	*West Virginia University*
William P. Armentrout	*Green Bank Observatory*
Thomas M. Bania	*Boston University*
Dana S. Balser	*National Radio Astronomy Observatory*
Matteo Luisi	*West Virginia University*
Trey V. Wenger	*University of Virginia*
D. Anish Roshi	*Arecibo Observatory*

Contact Person: Loren Anderson, Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26501; email: loren.anderson@mail.wvu.edu

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Abstract

Plasma of temperature $\sim 10^4$ K is created by OB stars and is therefore the signature of ongoing high-mass star formation. This plasma takes the form of discrete H II regions surrounding OB stars and diffuse ionized gas as part of the warm ionized medium (WIM). Understanding this plasma is the key to uncovering how massive star formation proceeds, determining the impact of massive stars on the interstellar medium (ISM), and revealing the lifecycle of gas in the ISM. Future surveys of H II regions and the WIM will allow us to trace star formation in the distant universe and will allow for detailed comparisons between the Milky Way and external galaxies.

Next-generation facilities studying H II regions and the WIM require good surface brightness sensitivity and the ability to tune to multiple spectral lines simultaneously. The proposed far-infrared Origins spacecraft would allow for efficient observations. In the radio regime, such observations are best done with large single-dish telescopes (e.g., the Green Bank Telescope or Arecibo Telescope) or compact arrays. Current designs for the ngVLA and SKA meet most of the requirements, but can be improved by the addition of a large single dish.

1. Introduction

This White Paper deals with observations of 10^4 K ionized gas in the Milky Way and external spiral galaxies. Such ionized gas is produced by (short-lived) massive OB stars, and therefore indicates active star formation. Almost a quarter of the gas mass of the Milky Way is ionized, and the 10^4 K gas makes up $\sim 90\%$ of the ionized gas mass; it is therefore important that we understand the physics and distribution of this phase of the interstellar medium (ISM).

The 10^4 K plasma can be separated into two components: discrete H II regions that surround massive OB stars and diffuse plasma that pervades the disk of spiral galaxies like the Milky Way. We will call the latter the "warm ionized medium" (WIM; Hoyle & Ellis 1963), though it is also sometimes known as "diffuse ionized gas" (DIG). H II regions have densities ranging from $\sim 1 - 10^5$ cm^{-3}, whereas typical densities in the WIM are much lower (~ 0.1 cm^{-3}).

Early work on H II regions, and most WIM studies, has been conducted by observing Hα emission. Although Hα is bright compared to other ionized gas tracers, it suffers from interstellar extinction, which drastically limits the distance to which the 10^4 K plasma in the inner Galaxy can be studied in the optical regime. Far-infrared (FIR) fine-structure lines such as [N II] at 122 and 205 μm are also efficient probes of this phase of the ISM, and are not affected by extinction.

Observations in the radio regime of thermal Bremsstrahlung and radio recombination lines (RRLs) allow for investigations of ionized gas throughout the Galactic disk and provide a natural complement to studies using Hα and FIR lines. The brightest RRLs are from hydrogen, but helium and carbon RRLs are also routinely detected. RRLs are found throughout the radio spectrum. Because the RRL intensity is only a weak function of frequency, multiple lines at nearby frequencies can be averaged to make a sensitive spectrum (Balser 2006).

The WIM can also be indirectly traced using observations of pulsars, whose time delay is proportional to the free electron column density. We will not discuss such observations here.

2. Current Observations

Observations of H II regions and the WIM can be separated into four broad categories: [1] studies of individual H II regions (Section 2.1); [2] surveys of large numbers of H II regions (Section 2.2); [3] large-scale surveys of the WIM (Section 2.3); and [4] studies of the WIM in external galaxies (Section 2.4).

2.1. Studies of Individual H II Regions

Observations of individual H II regions tell us about how star formation proceeds in the presence of strong ultraviolet radiation. Recent work has primarily been done at radio wavelengths. The literature on individual H II regions is difficult to adequately summarize because each region has unique characteristics. Recent results concern the fraction of escaping photons and their impact on the ISM (Luisi et al. 2016), and the impact of feedback (e.g., Lopez et al. 2011). The study of H II regions also provides clues as to how accretion continues after the central star has begun fusion (Peters et al. 2010; De Pree et al. 2013).

2.2. Surveys of H II Regions

Surveys of H II regions are key to understanding the structure of the Milky Way, including its chemical structure. H II regions trace ongoing massive star formation, and therefore their Galactic locations highlight the densest gas and their metallicities indicate present-day values. Observations of optical collisionally-excited lines (CELs) show that there is a Galactic radial gradient in the metallicity of H II regions (Shaver et al. 1983), a result confirmed by FIR observations of fine-structure lines (e.g., Simpson et al. 1995). Since metal CELs cool 10^4 K plasma, the electron temperature of an H II region reveals its current metallicity. H II region electron temperature gradients are similar to those seen in metal CELs (Balser et al. 2011), and may also reveal azimuthal metallicity structure (Balser et al. 2015).

The first "surveys" of H II regions were done by Sharpless (1953, 1959), quickly followed by Rodgers et al. (1960). These photometric studies of discrete Hα-emitting regions in optical photographic plates revealed a large population of H II regions around OB stars.

Large-scale RRL surveys of H II regions were done by Caswell & Haynes (1987); Lockman (1989). The study of IRAS data (Neugebauer et al. 1984) led to the discovery of "ultra-compact" H II regions (Wood & Churchwell 1989), which are angularly-small and therefore presumably young. An even earlier stage of "hyper-compact" H II regions are quite rare (Yang et al. 2019). The recent "H II Region Discovery Survey" (HRDS) encompasses multiple distinct surveys with the Green Bank Telescope (GBT Anderson et al. 2011, 2015, 2018), Arecibo Observatory (Bania et al. 2012), and the Australia Telescope Compact Array (Brown et al. 2017; Wenger et al. 2018). Together, these surveys have more than doubled the number of known Galactic H II regions, to over 2000.

Blind radio continuum surveys of the Galactic plane have the ability to detect large numbers of Galactic H II regions. The most recent large-scale radio continuum survey geared toward H II region detection is the 5 GHz VLA Co-Ordinated Radio 'N' Infrared Survey for High-mass star formation (CORNISH; Hoare et al. 2012). It detected hundreds of compact H II regions and H II region candidates (Purcell et al. 2013).

2.3. Large-scale Surveys of the WIM

The WIM fills the disk of spiral galaxies like the Milky Way. The Wisconsin H-α Mapper survey (WHAM; Haffner et al. 2010) mapped the entire sky at $\sim 1^\circ$ angular resolution, providing a large-scale view of the WIM. From these and similar observations we have learned that the WIM has a vertical scale height of 1.5 kpc and is the dominant form of hydrogen

1 kpc above the plane (Reynolds 1989). The existence of ionized hydrogen far off the disk implies that the ISM is porous.

Heterodyne FIR receivers allow for observations of the WIM at high spectral resolution, which is important for separating components kinematically. The *Herschel* GOT C+ survey (Langer et al. 2011) used spaced observations along the Galactic plane to investigate the distribution of ionized carbon in the Milky Way disk.

At radio wavelengths, the WIM is most often studied using RRLs, and there have been numerous large-scale RRL surveys of the WIM. Perhaps the first such survey was done by Lockman (1980), who used sparsely-sampled RRL observations in the Galactic plane. Other RRL surveys of the WIM (e.g., Roshi & Anantharamaiah 2000; Roshi & Anantharamaiah 2001; Baddi 2012) are generally at low angular resolution and low frequencies. Heiles et al. (1996) used the Hat Creek Radio Observatory to observe RRLs off the Galactic plane near 1.4 GHz. They found evidence for extraplanar gas that appears to be associated with massive star formation in the plane.

Only recently have researchers created fully-sampled maps of RRL emission. These maps allow us to determine the WIM distribution and kinematics. The Survey of Ionized Gas in the Galaxy, Made with the Arecibo telescope (SIGGMA; Liu et al. 2013) is a beam-sampled RRL survey of the $31^\circ < \ell < 70^\circ$, $|\,b\,| < 1.5^\circ$. Alves et al. (2015) extracted RRL data from the bandpass of the Hi-Pass survey (Staveley-Smith et al. 1996, 1998) to produce maps at $15'$ spatial resolution and 20 $\mathrm{km\,s^{-1}}$ spectral resolution. An ongoing GBT Diffuse Ionized Gas Survey (GDIGS) will produce the most sensitive RRL maps in existence over $-5^\circ < \ell < 32^\circ$, $|b| < 0.5^\circ$ (Figure 1). GDIGS maps are Nyquist-sampled at $1'$ spatial resolution (with a $\sim 3'$ beam) at a native spectral resolution of 0.2 $\mathrm{km\,s^{-1}}$. The beam size is ideal for mapping large areas of the sky in a reasonable amount of telescope time, and for investigating faint signals from diffuse gas. Such surveys allow us to determine the connection between the WIM and high mass star formation.

2.4. Studies of the WIM in External Galaxies

Observations of H II regions and the WIM in external galaxies trace ongoing star formation in nearby galaxies. For dense clusters with significant extinction, radio observations are especially valuable. Anantharamaiah et al. (2000) combined both RRL and continuum data at several different frequencies to constrain models of these young massive star clusters. Balser et al. (2017) used the upgraded Very Large Array to detect RRL emission in the nearby galaxy IC 342 for the first time and revealed thermal emission to the east and west of the nuclear star cluster that was associated with giant molecular clouds. The best fit model is a collection of many hundreds of compact (~ 0.1 pc) H II regions ionized by an equivalent of ~ 2000 O6 stars. Luisi et al. (2018) showed that RRL emission from normal nearby spiral galaxies can be detected by existing facilities in reasonable integration times $\sim$10 hours.

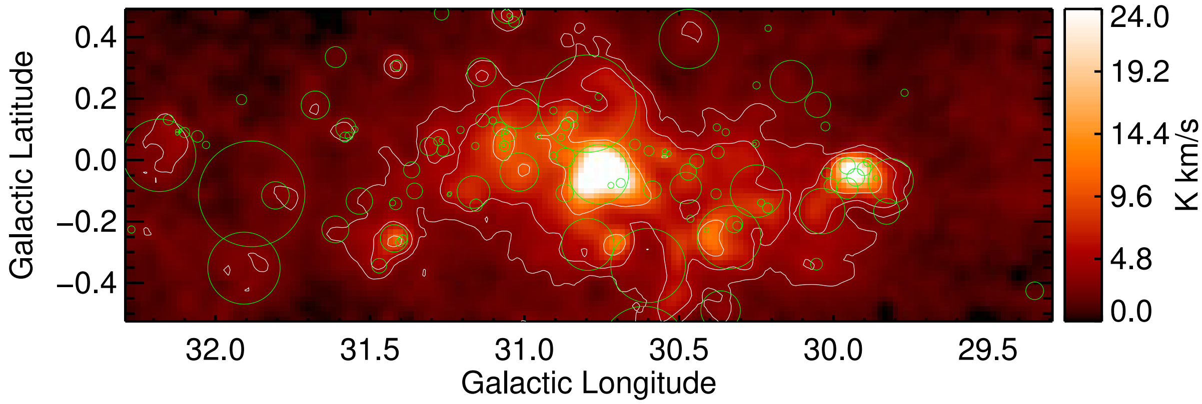

Figure 1: GDIGS integrated intensity (moment 0) map of a portion of the Galactic plane. Contours are at levels of 3,5, and 10 K $\mathrm{km\,s^{-1}}$. Green circles enclose known H II regions from Anderson et al. (2014). There is evidence for significant diffuse ionized gas outside discrete H II regions.

3. Outstanding Questions

There are a number of outstanding questions in studies of H II regions and the WIM:

1. How many Galactic H II regions are there and what are their luminosity and age distributions? Answering these questions will allow us to place the Milky Way into a broader galactic context.

2. What is the structure of the Milky Way, including its chemical structure? The Galactic metallicity gradient reflects generations of stellar processing. The parameters of this gradient are important for detailed chemical models of the Galaxy's formation and evolution.

3. What are the distribution and properties of the WIM in the plane of spiral galaxies (and the Milky Way)? Why is the ionization state of the WIM different from that of H II regions if the source of the WIM is massive stars? How are the distribution and properties of the WIM related to ongoing massive star formation? The WIM provides a link between ongoing high-mass star formation and gas that will cool and form future generations of stars.

4. Can we use observations of the WIM and H II regions in external galaxies to determine their star forming properties? FIR lines are now routinely used to determine the star formation rate of redshifted galaxies. RRLs can also be used to provide an extinction-free tracer of star formation, allowing us to verify the previous work on Hα.

4. Recommendations

To answer the above questions, future facilities should have:

1. broad bandpasses and the ability to simultaneously tune to many spectral lines;
2. large collecting area and good surface brightness sensitivity; and
3. high angular resolution.

The first recommendation allows for simultaneous observations of multiple spectral lines. This is important in the optical and FIR, as line ratios provide diagnostics on the properties of the plasma. Since RRLs are found throughout the radio regime, a broad bandpass allows for the simultaneous observation of many RRLs. Data on H II regions and the WIM often come "for free" since RRLs are found across the radio spectrum and can be put in any free spectral windows. For interferometers, wide bandpasses allow for sensitive radio continuum observations simultaneously with any spectral lines. Thus, with careful bandpass tuning, one can in principle obtain information on 10^4 K plasma from any radio observation.

The second goal is important for studies of resolved objects. This includes studies of the WIM, but also observations of many Galactic H II regions and the RRL emission from external galaxies. Next-generation FIR facilities would benefit from large primary mirrors. In the radio, uniform surface brightness sensitivity is obtained by good $u - v$ plane coverage. "Short-spacing" information, i.e. from large single-dish telescopes, is especially important for studies of the diffuse WIM.

High angular resolution will allow for detailed studies of H II regions in external galaxies. The resolution of such observations should be sufficient to avoid blending of nearby H II regions, and to separate H II region emission from that of the WIM.

Future observatories will revolutionize the study of H II regions and the WIM. The planned Origins instrument would be an excellent facility for such studies. RRL emission is faint, and therefore large collecting areas are required. The current ngVLA design meets goals 1 and 2 above. Balser et al. (2018) discuss ngVLA RRL observations in detail. To increase the surface brightness sensitivity and increase the efficiency of the ngVLA, it will be beneficial to also include a large single-dish telescope (as argued by Frayer 2017). The SKA, with its larger number of dishes, may have better surface brightness sensitivity than the ngVLA.

The existing GBT and Arecibo telescopes are excellent instruments for studies of H II regions and the WIM. Upcoming multi-pixel systems such as Focal L-band Array for the GBT (FLAG) and Advanced Cryogenic L-band Phased Array Camera for the Arecibo Radio Telescope (ALPACA) will significantly increase the survey speed of both these telescopes at 1.4 GHz. Installing multi-feed systems at other frequencies would significantly increase survey speeds.

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