Warm Ionized Gas on the Outskirts of Active and Star-Forming Galaxies

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Abstract. The preliminary results from a deep emission-line search for warm ionized material in the halos of nearby active and star-forming galaxies are presented. The origin of this gas is discussed in the context of galaxy formation and evolution.

1. Introduction

The need for a comprehensive survey of the warm ionized medium in the local universe can hardly be overstated. This gas phase may contribute significantly to the local baryon budget (e.g., Fukugita, Hogan, & Peebles 1998). While an important fraction of this material is almost certainly in the form of intergalactic clouds not related to any individual galaxy, some may inhabit the dark matter halos of galaxies.

This gas phase is a key witness of galaxy formation and evolution. In a hierarchical CDM universe (e.g., Jenkins et al. 1998) most of the activity associated with galaxy formation takes place at $z \gtrsim 1$, except perhaps in the outer reaches of galaxies where “primordial” gas may still be accreting today. Some of this material will necessarily be ionized by the metagalactic ionizing radiation, and possibly by local sources of ionizing radiation such as active galactic nuclei (AGN) and starburst galaxies. In this picture, the warm ionized gas on the outskirts of galaxies represents left-over debris associated galaxy formation.

The warm ionized gas is an excellent probe of the feedback processes taking place in galaxies. Ionizing radiation and energy injection from star-forming regions and quasars may severely limit the amount of star formation and affect galaxy evolution. Galactic winds may blow out through the gaseous halos of galaxies and into the IGM, enriching and heating the intergalactic environment in the process. These winds may be responsible for the well-known mass-metallicity relation in galaxies (e.g., Larson & Dinerstein 1975; Vader 1986; Franx & Illingworth 1990). The warm ionized gas phase in these winds is primarily made of the cool/warm ISM originally belonging to the host galaxies.

This paper describes the preliminary results of a deep emission-line survey of the local universe. The main goals of this survey are to search for warm ($T \approx 10^4$ K) ionized gas on the outskirts of nearby galaxies, and study the properties of this gas to find out its origin and overall importance. For lack of space, the present discussion focuses only on the warm ionized halos of active and star-forming galaxies; we do not discuss our recent results on the warm ionized
edges of disk galaxies and on isolated extragalactic H I clouds (this last topic is discussed by S. Vogel in this volume; see also Weymann et al. 2001).

2. Observations

Over the past few years, our group has obtained deep emission-line images of several starburst and active galaxies using the Taurus Tunable Filter (TTF)\textsuperscript{1} on the 3.9m Anglo-Australian and 4.2m William Herschel Telescopes. This instrument is uniquely suited for this type of survey, combining wide field of view with outstanding narrow-band imaging capabilities over a broad range in wavelength (3500 Å – 1.0 μm) and bandpass (10 – 100 Å). The TTF uses high-performance, low-order Fabry-Perot etalons equipped with long-range piezo-electric transducers now sufficiently reliable to allow the parallel plates to be scanned over a physical spacing of 4 μm (5 wavelengths or 10 interference orders in the I band) and to allow parallelism to be maintained down to spacings of ~ 1 μm. To maximize sensitivity to faint flux levels, we are using the TTF in the so-called “charge shuffling/frequency switching” mode. The basic idea is to move charge up and down within the detector at the same time as switching between two discrete frequencies with the tunable filter. The chip is read out only once. As a result, the TTF can produce simultaneous continuum and emission-line images that reach flux levels of order a few x 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} (ε_m ~ 1 cm^{-6} pc), an order of magnitude fainter than typical narrow-band images published on normal or active galaxies. Many of the images were obtained in a straddle mode, where the off-band image is made up of a pair of images that “straddle” the on-band image in wavelength (e.g., λ_1 = 6500 Å and λ_2 = 6625 Å for rest-frame Hα); this greatly improves the accuracy of the continuum removal since it corrects for slopes in the continuum, underlying absorption features, etc.

Complementary long-slit optical spectra were also obtained for some objects to clarify the origin and source of ionization of the warm ionized material. When available, multiwavelength and HST data were used to track the hot (ROSAT, Chandra) and relativistic (VLA) gas phases and improve on the spatial resolution of our ground-based data.

3. Results

3.1. Normal Star-Forming Disk Galaxies

This portion of the survey is part of Scott Miller’s Ph.D. thesis at the University of Maryland (Miller 2001). Twenty non-active, non-interacting spirals were selected for this study based on their proximity (z < 0.01; for good spatial resolution: < 200 pc arcsec^{-1}), angular size (< 10' = field of view of the TTF), and inclination (i > 75°).

Thick ionized disks and/or filamentary structures are detected out to a few kpc from the planes of several galaxies in our sample. This is consistent with the results from earlier imaging studies (e.g., Rossa & Dettmar 2000; Collins &

\footnote{http://www.aao.gov.au/ttf}
Figure 1. Multi-line imaging of normal edge-on disk galaxies. NGC 891. (left) Hα. (center) [N II] λ6583. (right) [N II] λ6583/Hα ratio map.

Rand 2001, and references therein). Both the mass and extent of the extraplanar material in these galaxies appear to be correlated with the local surface density of star formation activity in the disk.

Multi-line imaging with the TTF (see Fig. 1 for one example) indicates that the emission-line ratios of the high-|z| ionized gas differ considerably from those of H II regions. For instance, the [N II] λ6583/Hα ratio in the extraplanar gas often exceeds unity. Our complementary long-slit data confirm these results, showing a general increase of the [N II]/Hα, [S II]/Hα, and [O I]/Hα ratios with increasing heights in most galaxies. The trends seen in these ratios of collisionally-excited lines to recombination lines indicate that the amount of heating per ionization increases with increasing vertical distance from the disk.

We are currently modelling these variations using the photoionization code CLOUDY. Radiation from OB stars in the disk appears to be capable of explaining most of these line ratios, as long as one takes into account the multi-phase nature of the ISM, the possible depletion of certain gas-phase abundance of metals onto dust grains, and the absorption and hardening of the stellar radiation field as it propagates through the dusty disk. However, positive vertical [O III]/Hα gradients in a few galaxies suggest the presence of an additional source of ionization in these objects (e.g., shocks, turbulent mixing layers).
3.2. Starburst and Active Galaxies

Over the history of the universe, AGN- and starburst-driven winds may have had a strong cumulative impact on the thermal and chemical evolution of galaxies and their environment (see Cecil 2000, Veilleux 2000, Veilleux et al. 2001, and contributions from T. Heckman, C. Martin, and M. Lehnert to this volume for a summary of the situation). So far, very little is known on high-z winds (Pettini et al. 2000 and references therein). Studies of their local counterparts have the clear advantage of increased spatial resolution and sensitivity to faint low-surface-brightness features. The recent detection of Hα filaments (the “cap”) and diffuse soft X-ray emission out to 11.6 kpc to the north of the prototypical starburst/superwind galaxy M82 emphasizes the need for surveying large areas around superwind galaxies to constrain the size, energetics, and impact of these superwinds. The radial velocity of the cap (50 – 200 km s\(^{-1}\)) exceeds the local escape velocity. Thus, the blowout of the nuclear superwind and the cap of Hα-emitting plasma that delineates its most distant optically visible component is likely to inject metal-enriched matter into the intergalactic medium of the M81/M82/NGC 3077 system (Devine & Bally 1999; Lehnert, Heckman, & Weaver 1999). The existence of a 30-kpc limb-brightened “double-bubble” system in Arp 220 (Heckman et al. 1987, 1996), powered by a luminous starburst or dust-enshrouded QSO, is another indication that superwinds often have large “spheres of influence”.

Arguably the most spectacular example of a superwind (superbubble) in a nearby galaxy lies in the core of NGC 3079, an otherwise normal looking edge-on SBc galaxy at 17 Mpc. Detailed Fabry-Perot, HST, and VLA studies of this galaxy by our group (Veilleux et al. 1994; Cecil et al. 2001) reveal a system of ionized strands \( \sim 0.3 \) (25 pc) wide which emerge from the nuclear region as five distinct gas streams with velocity gradients and dispersions of hundreds of km s\(^{-1}\) (Fig. 2). The pattern of magnetic fields and the gas kinematics suggest a wind of mechanical luminosity \( 10^{43} \) erg s\(^{-1}\) that has stagnated in the galaxy disk at a radius \( \sim 800 \) pc, flared to larger radii with increasing height as the balancing ISM pressure reduces above the disk, and entrained dense clouds into a vortex. The observed sphere of influence of this wind is at least \( \sim 3–5 \) kpc, based on the detection of X-shaped optical filaments and X-ray emission extending on that scale. But circumstantial evidence for a much larger outflow exists in this galaxy. Irwin et al. (1987) have indeed argued that the outflow extends out to at least \( \sim 50 \) kpc, based on the presence of an elongated HI tail in the nearby dwarf S0 galaxy NGC 3073 which is remarkably aligned with the nucleus of NGC 3079. Irwin et al. argue that the ram pressure from a wind freely expanding (\( n \propto r^{-2} \)) out of the nucleus of NGC 3079 would be more than sufficient to produce the H I tail. The existence of this purported giant wind has not yet been confirmed by other means, however.

In some AGN and starbursts, the intense nuclear radiation field leaks out of the center and photoionizes the material on the outskirts of the host galaxies. The geometry of the nuclear region (e.g., opening angle of the accretion disk in AGN, shape of the star-forming molecular disk in nuclear starbursts) and nature of the host galaxy (cool disk galaxy vs. hot spheroid-dominated system) determine the angular dependence of the ionizing radiation field on large scales. One of the best cases of such “ionization cone” is seen in the Seyfert galaxy...
NGC 5252. The line-emitting gas in this galaxy is distributed in a wide-angle bicone with opening angle of $\sim 75^\circ$ that extends over $\sim 40$ kpc and consists of a complex network of filamentary strands (Tadhunter & Tzvetanov 1989; Wilson & Tzvetanov 1994). A detailed Fabry-Perot study of this region (Morse et al. 1998) shows complex kinematics which are best explained as the superposition of two inclined rotating disk, probably originating from a past galaxy merger event.

Our TTF survey has revealed new examples of large-scale ionization structures. Figure 3 shows our recent results on the prototypical Seyfert 2 galaxy NGC 1068. Here, a line-emitting filamentary complex is detected at H{$\alpha$} out to $\sim 12$ kpc from the nucleus, slightly beyond the H I edge of this galaxy [as measured from the recent H I maps of Brinks (2001)]. Multi-line imaging of this galaxy with the TTF detects this complex in several other lines including [N II] $\lambda$6583, [S II] $\lambda\lambda$6716, 6731, and [O III] $\lambda 5007$. The biconical geometry of the complex and the relative strengths of the emission lines suggest that the central AGN is contributing to the ionization of this material. This bicone is roughly aligned with the nuclear outflow/jets and ionization cone seen on smaller scales (e.g., Cecil, Tully, Bland 1990; Macchetto et al. 1994). It is not clear at present whether the line-emitting filaments represent disk material that is simply being illuminated by the AGN or whether the ionized gas is taking part in a dynamical event.

Figure 4 shows a deep H{$\alpha$} + [N II] $\lambda$6583 + continuum image of the Seyfert 1 galaxy NGC 7213 obtained with the TTF on the AAT. This image reveals the presence of a line-emitting filament located $\sim 19$ kpc from the nucleus, well outside the optical radius of this galaxy. This filament was independently discovered by Hameed et al. (2001). Our data show that the [N II]/H{$\alpha$} ratio in the filament is unlike what is typically seen in H II regions. Multi-line imaging
Figure 3. NGC 1068 in Hα. Hα emission is detected for the first time out to the H I edge of this galaxy. The emission is more visible in the NE (upper left) quadrant; fainter emission is also detected SW of the nucleus. The field of view of this image is about 6′3 or 26 kpc at the distance of NGC 1068. (Shopbell, Bland-Hawthorn, & Veilleux 2001, in prep.).
slightly shifted in velocity space suggests that the warm gas is blueshifted by 100 – 150 km s\(^{-1}\) with respect to systemic velocity. A deep long-slit spectrum obtained with the MSSSO 2.3m telescope confirms these results. The recent study of NGC 7213 by Hameed et al. (2001) reveals a highly disturbed H I system suggesting a past merger event. The line-emitting filament seems to coincide spatially and kinematically with the main H I filamentary structure.

A recent TTF study by our group of the radio-quiet quasar MR 2251–178 has revealed a very extended nebula centered on and photoionized by this quasar (Shopbell, Veilleux, & Bland-Hawthorn 1999). A spiral-like complex extending more or less symmetrically over \(\sim 200\) kpc is detected in our TTF H\(\alpha\) image (Fig. 5; see also Shopbell, Veilleux, & Bland-Hawthorn 1999). Narrow-band images obtained at slightly different wavelengths reveal a large-scale rotation pattern which is in the opposite sense as that seen in the inner region of the galaxy (see also Bergeron et al. 1983; Nørgaard-Nielsen et al. 1986). As discussed in detail in Shopbell et al., the large and symmetric morphology of the gaseous envelope and its smooth large-scale rotation suggest that the envelope did not originate with a cooling flow, a past merger event, or an interaction with any of the galaxies in the field. Shopbell et al. favor a model in which the extended ionized nebula resides within a large complex of H I gas centered on the quasar.

3.3. Summary and Further Improvements

We have presented some results from our on-going deep emission-line survey of nearby galaxies with the TTF on the AAT and WHT. Our preliminary data reveal filamentary complexes extending a few kpc above and below the disks of normal star-forming galaxies. In active and starburst galaxies, ionized filaments are sometimes seen extending out to several tens of kpc. Multi-line imaging of these objects reveals line ratios which are not H II region-like. An early analysis of our results on normal disk galaxies suggests that the extraplanar gas is primarily photoionized by the highly diluted and filtered radiation from OB stars in the disk. In active galaxies, the central engine appears to be the primary source of ionization of the extended nebula.

These data are providing new constraints on the impact of star formation and nuclear activity on the host galaxies and their environment. The implementation of a nod-and-shuffle mode (where the telescope points alternately on target and on a reference sky position without reading out) and a broad off-band mode (where the off-band bandpass can be chosen to be as large as 100 Å therefore reducing the required exposure time in this band) on the TTF should allow us to significantly improve the sensitivity of our experiment.

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Figure 4.  Hα + [N II] λ6583 + continuum image of NGC 7213. A line-emitting filament is detected 19 kpc SW of the nucleus, well beyond the optical extent of NGC 7213. The existence of this filament has been independently confirmed by Hameed et al. (2001).
Figure 5. Deep Hα image of the field surrounding the quasar MR 2251–178. A bright star (S), a nearby cluster galaxy (G1), and a number of emission-line knots from Macchetto et al. (1990) have been labeled. North is up and east to the left. The lowest contour in this figure represents a surface brightness level of $\sim 1 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. See Shopbell, Veilleux, & Bland-Hawthorn (1999) for more detail.
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