Diffuse Ionized Gas in Edge-on Galaxies

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Abstract

We review observations of diffuse ionized gas (DIG) in edge-on spiral galaxies. Deep imaging has revealed a variety of morphologies for "extraplanar" (above the HII region layer) or "halo" DIG: some show widespread prominent layers of truly diffuse gas and filamentary structures, others show just one or a few patches of extraplanar emission, while still others show no detectable extraplanar DIG at all. The key galactic property which appears to govern the prominence of the DIG layer is the star formation activity. Smaller scale connections between DIG and local star formation activity can be seen in some of the galaxies.

DIG halos are also related to radio continuum, X-ray and HI halos. Those galaxies with the most prominent DIG layers also have the most prominent radio halos. In NGC 891, there are spatial correlations between extraplanar DIG, radio emission, X-ray emission and HI, and these in turn are related to the underlying disk star formation activity.

Progress on identifying the sources of ionization and heating of the gas has come from spectroscopy, imaging in different emission lines, and Fabry-Perot observations. By comparing with theoretical predictions, much evidence is found for photo-ionization by disk stars as the primary ionization and heating mechanism, but recent observations are beginning to point towards the need for additional sources of ionization and/or heating.

Keywords: galaxies: ISM — galaxies: halos — galaxies: spiral — galaxies: structure — radiative transfer

1 INTRODUCTION

With the advent of the AAO-UKST Galactic Plane Hα survey and the several other Galactic surveys discussed in this volume, an opportunity arises for progress in understanding the origin, structure, and ionization of DIG through the comparison of these surveys with observations of external edge-on galaxies. These galaxies offer the advantage of allowing the entire DIG layer to be quickly imaged (albeit at relatively low linear resolution), while avoiding the difficulty inherent in Milky Way observations of translating angular heights of emission to physical heights. Studies of the diffuse ionized layer of the Milky Way will allow, for example, the vertical structure of the layer and the dependence of line ratios on height from the Galactic plane and on the underlying disk environment to be compared with results from external edge-ons. The importance of DIG as an ISM component and the leverage it provides on understanding the ISM as a whole is discussed elsewhere in this volume by Reynolds, Ferrara, Elmegreen and others. The goal of this review is to summarize our understanding of DIG in edge-on galaxies at the time when these surveys are getting underway.

TABLE 1
COMPARISON OF EXTRAPLANAR DIG PROPERTIES WITH TRACERS OF STAR FORMATION

Galaxy	Type	Dist. (Mpc)	Adopted incl.[a]	DIG morphol.	L_{FIR} [b] (10^{43} erg s^{-1})	L_{FIR}/D_{25}^2 (10^{40} erg s^{-1} kpc^{-2})	DIG ref.
NGC 3079	Sc	17.3	84	bright diffuse+filaments	14	8.9	(1)
NGC 5775	Sc	26.7	85	many bright fil.	8.6	8.1	(2)
Milky Way	Sb	...	...	diff.+fil.	3.8[c]	3.0	(3)
NGC 891	Sb	9.5	89	bright diff.+fil.	3.1	2.2	(4)
NGC 4013	Sbc	17.0	90	faint diff.+fil.	1.4	2.6	(5)
NGC 4631	Sd	7.5	85	bright diff.,patchy	2.0	1.8	(6)
NGC 55	Sm	7.5	79	bright diff.+fil.	0.15	0.5	(7)
NGC 4302	Sc	16.8	90	faint diff.	<1.2[d]	<2.3	(5)
NGC 5907	Sc	14.9	86	no halo DIG	2.0	0.8	(5)
UGC 10288	Sc	31.5	86	3 or 4 plumes	0.8	0.4	(5)
NGC 4565	Sb	9.7	86	no halo DIG	0.5	0.3	(6)
NGC 5746	Sb	29.4	86	no halo DIG	1.4	0.2	(5)
NGC 4244	Scd	3.1	88	no halo DIG	0.1	0.01	(8)
NGC 5023	Scd	6	87	1 or 2 plumes, 1 faint patch	<0.01[e]	<0.09	(5)
NGC 4217	Sb	17.0	86	2 faint patches	<0.08[e]	<0.12	(5)
UGC 4278	Sd	10.6	87–90	2 plumes+patches	<0.03[e]	<0.04	(5)
NGC 4762	S0	16.8	90	no halo DIG	<0.08[e]	<0.15	(5)

Values of D_{25} are from de Vaucouleurs et al. (1991)

References: (1) Veilleux et al. (1995); (2) Dettmar (1992); (3) Reynolds (1993); (4) Rand, Kulkarni, & Hester (1990), Dettmar (1990); (5) Rand (1996); (6) Rand, Kulkarni, & Hester (1992); (7) Ferguson, Wyse, & Gallager (1996); (8) Walterbos (1991)

[a]References for inclinations of previously observed galaxies: NGC 3079 (Irwin & Seaquist 1991), NGC 5775 (Dettmar 1992), NGC 891 (Swaters 1994), NGC 4631 and NGC 4565 (Rand, Kulkarni, & Hester (1992), NGC 4244 (Walterbos 1991)

[b]For external galaxies, from Rice et al. (1998) where possible; otherwise from the IRAS Cataloged Galaxies and Quasars

[c]From Cox & Mezger (1989)

[d]The *IRAS* source is compact and between NGC 4302 and its companion NGC 4298. These are separated by 2.4', so the *IRAS* source is probably a blend of emission from both galaxies.

[e]Not detected by *IRAS*. These are estimated 3σ upper limits assuming that the detection limit in these fields was typical of the *IRAS* observations. None of these galaxy fields was missed by *IRAS*.

2 DIG MORPHOLOGY

NGC 891, having an optical appearance similar to the Milky Way, and being nearby ($D = 9.5$ Mpc) and almost perfectly edge on (Swaters 1994), was the first target in the search for extraplanar DIG layers (Rand, Kulkarni, & Hester 1990; Dettmar 1990). There, a bright, widespread DIG halo was found, showing truly diffuse emission as well as several quasi-vertical filaments of height 2–3 kpc. The halo could be traced up to $z = 3.5$ kpc, but recent deep spectroscopy (Rand 1997; see below) shows that it extends to at least $z = 5.5$ kpc. Furthermore, the spectra confirm the earlier result that there are two vertical components to the emission, with electron density scale heights (assuming that the gas temperature and filling factor are constant with z) of 1 kpc and 5–6 kpc. The emission is concentrated to within about $R = 8$ kpc of the center of the galaxy, with the brightest region at about $R = 5 - 8$ kpc on the north side and a rather sharp cutoff beyond this region. Disk star formation, as traced by [C II] 158μm emission (Madden et al. 1992), shows a radial profile with very similar asymmetries (Rand 1994).

Almost without exception, the Hα filaments have their footprint in bright HII regions in the disk (Rand 1994). Some are quite narrow and may be walls of chimneys (Norman & Ikeuchi 1989), others are broader and may be “ionization cones”: regions where relatively exposed O and B stars have been able to ionize large volumes of diffuse gas above and below the midplane (Miller & Cox

1993, Dove & Shull 1994). In the case of the former, the connection with HII regions suggests that star formation persists in these ~ 1 kpc regions of disk for at least as long as the $\sim 10^7$ yr dynamical time (Norman & Ikeuchi 1989) to produce the chimneys. This connection between filaments and HII regions is also seen in NGC 2188 (Domgörgen, Dahlem, & Dettmar 1996) and NGC 55 (Ferguson, Wyse, & Gallagher 1996; Wyse, this volume).

Since these observations, over a dozen edge-ons have been observed with similar sensitivity, with the result that bright, extended DIG layers as in NGC 891 are the exception rather than the rule (Table 1). Other galaxies with bright layers include NGC 4631 (although only above the central few kpc; Rand, Kulkarni & Hester 1992) NGC 5775 (Dettmar 1992), and NGC 3079 (Veilleux, Cecil, & Bland-Hawthorn 1995). However, most galaxies seem to show only one or a few isolated patches or filaments of emission above the HII region layer, while some show no extraplanar DIG at all (Rand 1996). The prominence of the extraplanar DIG emission is related to the star formation activity in the disk. Insofar as far infrared luminosity (L_{FIR}) is a tracer of star formation activity (debate continues on what fraction of the emission comes from dust heated by the ISRF; however, one cannot use Hα emission as a star formation tracer because of the severe extinction problem), then the galaxies with high surface densities of star formation (L_{FIR}/D_{25}^2) generally have the brightest and most prominent extraplanar DIG layers (Rand 1996). This general connection is strengthened by the afore-mentioned correlation of halo DIG and disk [C II] emission profiles in NGC 891 and the filament-HII region associations, and it is probably more accurate to say that active star-forming regions tend to have associated extraplanar DIG.

Current directions in this area include attempts at better characterization of the background emission to allow heavier smoothing, thus making possible searches for emission at much fainter levels. Examples are the "shift and stare" technique (Donahue, Aldering, & Stocke 1995) and "charge shuffling" (Bland-Hawthorn, this volume). In this way, one can hope to determine the extent of halos at low column densities and their possible relevance as QSO absorption line systems.

3 DIG AND OTHER GASEOUS HALOS

The galaxies with the brightest extraplanar DIG layers also tend to have bright and extended radio continuum halos (Rand 1996). Examples are NGC 891 (e.g. Dahlem, Dettmar, & Hummel 1994), NGC 4631 (e.g. Golla & Hummel 1994), and NGC 5775 (Dettmar 1992; Duric, Irwin, & Bloemen 1996). At the other end of the scale, NGC 4244, with no indications of extraplanar DIG (Walterbos & Braun 1996), was not detected at all in radio continuum (Hummel, Sancisi, & Ekers 1984). Dettmar (1992) reports an association between filaments of radio and Hα emission in the halo of NGC 5775. One might expect an Hα-radio correlation if magnetic fields associated with the thermal gas serve to confine the cosmic-ray electrons as they try to escape the disk (N. Duric, pers. comm.). Observational connections between radio halo and star formation distributions in edge-ons has also been discussed by Dahlem, Lisenfeld, & Golla (1995). Most of the galaxies in Table 1 have not been observed with sufficient sensitivity and resolution to search for a radio halo.

Diffuse X-ray halo emission is also difficult to detect and has been searched for in only a few of these edge-ons with ROSAT. NGC 891 (Bregman & Pildis 1992; Bregman & Houck 1997) and NGC 4631 (Wang et al. 1994) are notable for having relatively bright X-ray halos occupying about the same radial range as the Hα halos. However, this trend is not perfect: patches of diffuse halo X-ray emission have been found in NGC 4565 (Vogler, Pietsch, & Kahabka 1996), which shows no extraplanar DIG.

NGC 891 has a very thick disk of 21-cm emission, and a careful study of the origin of this high-z gas has been carried out by Swaters (1994). The kinematic information allows inner-disk high-z gas, which may be accelerated by supernova activity, to be distinguished from outer-disk gas, which may be due to warps and flares. The result is that the most prominent inner-disk high-z emission is coincident with the brightest region of halo DIG and radio emission, sitting above the brightest [C II] 158μm emission in the disk (all at about $R = 5 - 8$ kpc on the north side). This HI is detected up to 2.5 kpc above the disk. There does not seem to be a good correlation between individual HI and Hα filaments, however, although the lower (20") resolution of the HI may hamper the comparison. Other bright star forming edge-ons (NGC 3079, NGC 5775) show HI arcs, shells and filaments extending several kpc from the plane (Irwin & Seaquist 1990; Irwin 1994). Connections between these and Hα features are not yet clear.

The emergent scenario, then, which needs to be tested further, is that star formation activity, when sufficiently intense, leads to the elevation of gas from the thin, star-forming layer, through chimneys and superbubbles, leading to halo DIG, HI and X-ray emission. Meanwhile, diffusion and possibly localized regions of convection of cosmic rays produced in supernovae (e.g. Duric, Irwin, & Bloemen 1996) produce cosmic ray halos, traceable through radio continuum emission.

4 EMISSION LINE RATIOS AS DIAGNOSTICS OF IONIZATION AND HEATING

In the Reynolds layer, photo-ionization by massive stars in the disk is considered the most likely primary ionization mechanism (Reynolds, this volume). The available energy easily satisfies that required to maintain the layer, and photo-ionization models [e.g. Mathis 1986; Sokolowski 1994 (partially reproduced in Bland-Hawthorn, Freeman, & Quinn 1997)] have been the most successful in explaining the behavior of line ratios (enhanced [S II]$\lambda\lambda$6716, 6731/Hα, [N II]λ6583/Hα, very weak [O I]λ6300/Hα, [O III]λ5007/Hα relative to HII regions are due to dilution of the stellar radiation as it propagates away from the Galactic plane). However, there are observations that these models cannot explain – one of which is the weakness of He Iλ5876/Hα (Reynolds & Tufte 1995; Reynolds, this volume), a ratio with a fairly straightforward interpretation in terms of the hardness of the ionizing radiation [see also Heiles et al. (1996) for an even more extreme result from radio recombination lines]. The He I emission is much weaker than expected from models given the high [N II]/Hα and [S II]/Hα values [see Domgörgen & Mathis (1994)]. The forbidden lines are highly temperature sensitive and their interpretation is complicated by issues of abundances, gas heating, and depletion of important coolants such as Fe, Si, and Ca (Sokolowski 1994). But regardless of the forbidden lines, the low He I/Hα is problematic in itself and may indicate that we do not understand stellar atmospheres in the extreme UV well enough (see e.g. Cassinelli et al. 1995), and/or which spectral types of massive stars are most important for the ionization (Reynolds & Tufte 1995; Heiles et al. 1996).

It is also not clear to what degree other sources of ionization contribute: shocks (which may play a role in irregulars; Martin 1996), turbulent mixing layers (Slavin, Shull, & Begelman 1993), cooling fountain gas (Shapiro & Benjamin 1993) and decaying neutrinos (e.g. Sciama 1995).

In NGC 891, the run of [N II]/Hα vs. z at $R = 5$ kpc on the north side has been measured by Rand (1997). This shows a smooth increase with z, from 0.4 in the midplane to 1.4 at $z = 2$ kpc (east side of midplane) and $z = 4$ kpc (west side). Previous, less sensitive spectroscopy by Dettmar & Schulz (1992) and Keppel et al. (1991) also showed an increase with z for [N II]/Hα as well as [S II]/Hα. The same trend in [S II]/Hα was also seen in narrow-band images (Rand, Kulkarni, & Hester 1990). The spatial behavior is as expected in photo-ionization models (the ratios rise with distance from the disk ionizing sources as the radiation field is diluted) but values as high as 1.4 are difficult to explain (Sokolowski 1994). Note that in M31 (Walterbos, this volume) and the Milky Way, [N II]/Hα is roughly constant at only 0.3–0.5, and well modeled by Domgörgen & Mathis (1994). It is not clear whether the lower value is due to a less dilute radiation field, or whether features of some models of Sokolowski designed to raise the value, such as a very high upper IMF cutoff, do not apply in these cases.

He I is detected in NGC 891, but, as in the Reynolds layer, the weakness of He I/Hα implies a much softer spectrum than indicated by [N II]/Hα, and also softer than expected for a population of ionizing stars (Rand 1996). A measurement of the gas temperature would help in understanding the forbidden line strengths, but only upper limits exist from the non-detection of the [N II]λ5755 line: 13,000 K (east side) and 10,000 K (west side).

Veilleux et al. (1995) have formed an [N II]/Hα map of NGC 3079, where again there is a general increase with distance from HII regions, reaching similar values as in NGC 891.

Golla, Dettmar, & Domgörgen (1996) present long-slit spectra of NGC 4631, and again find an increase of [N II]/Hα and [S II]λ6716/Hα height from the plane. However, the rate of increase of the two ratios with z is about the same (both running from a minimum of about 0.13 in the plane to a maximum of about 0.5 at $z = 1$ kpc in their slit position "C"), whereas their models predict a stronger trend in [S II]/Hα than in [N II]/Hα (because of a more dramatic change in the predominant ionization state of S between HII regions and diffuse gas). The solution of this discrepancy is not clear, but again it points towards a departure from existing models.

Finally, Ferguson, Wyse, & Gallagher (1996) present Hα+[N II], [S II] and [O II]λ3727 images of NGC 55, and find that both [S II]/Hα+[N II] and [O II]/Hα+[N II] increase with height from the plane (like N and S, O becomes increasingly singly ionized with greater distance from the HII regions). The latter ratio shows a very strong contrast, from about 0.1 in the midplane to as high as 2 in the halo. Again, such high values are hard to explain.

Clearly, more work needs to be done to constrain the sources of ionization and heating. One approach is to model a combination of photo-ionized gas with shock-ionized gas using various shock speeds, and turbulent mixing layers of various temperatures, as has been done for the much brighter diffuse emission of irregulars by Martin (1996). While such composite models may be able to explain the observations, one still desires a physical scenario which joins these several processes together. For instance, in a model where the diffuse halos are fed by superbubble and chimney activity, what sort of shocks are predicted to run through the halo gas as a result, what sort of mixing interfaces should exist, and how might line ratios change with environment?

As for extra sources of non-ionization heating, possibilities include photoelectric heating from dust grains (Reynolds & Cox 1992) and the dissipation of turbulence (Minter & Balser 1997). The latter authors include a heating rate from turbulence derived from scintillation observations in a photo-ionization model of the DIG and can thereby explain simultaneously [S II]/Hα, [N II]/Hα, and [He I]/Hα at low-z in the Reynolds layer if the composite stellar temperature is low enough.

Acknowledgements

I would like to thank the organizers for a stimulating and well-run workshop, and the referee, R. Walterbos, for helpful comments.

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