Part IX

External Galaxies

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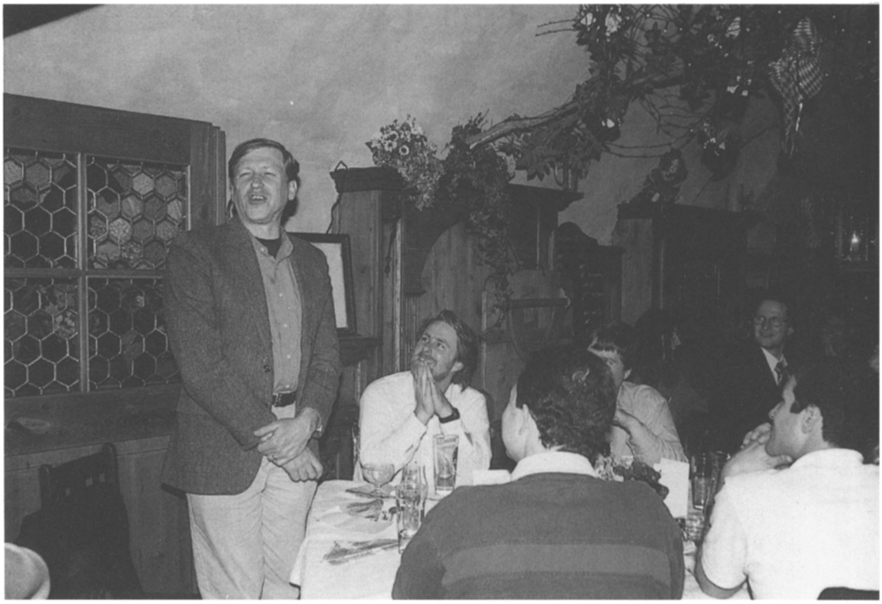

After-dinner speaker Jay Lockman attracts full attention ...

... with funny anecdotes about astronomers.

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Diffuse Ionized Gas in Halos of Spiral Galaxies

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Abstract. Over the last couple of years Diffuse Ionized Gas (DIG) has been identified as an important constituent of the interstellar medium (ISM) in the halos of spiral galaxies. Imaging in and spectroscopy of optical emission lines allow us to study the distribution and excitation of this gas with a spatial resolution not achievable for other phases of the ISM in external galaxies. Its origin and ionization is under debate and give important constraints for models of the ISM in general and on the large scale exchange of matter between disk and halo in particular. This review summarizes more recent observational results and compares them with model predictions. The data available now demonstrate that the presence of DIG in the disk-halo interface of spiral galaxies is related to star formation processes in the underlying disk. While photoionization by OB stars in the disk seems a viable source for the power required to ionize the DIG, additional processes are needed to explain some of the spectral features. The observed correlation with properties of the non-thermal radio continuum indicate that magnetic fields and cosmic rays could play a rôle for the physics of this medium.

1 Introduction

The detection of X-ray emitting gas in halos of late type spiral galaxies by ROSAT (Bregman and Pildis 1994, Wang et al. 1995, Vogler et al. 1996) provides important evidence for the long proposed scenario of a large scale exchange of matter between the interstellar medium (ISM) in galactic disks and their halos. This scenario is closely related to dynamical models of the ISM which also try to explain the formation of bubbles as, e.g., discussed in the contribution by Ikeuchi (1997). While the existence of X-ray halos supported by such processes was long expected, the presence of Diffuse Ionized Gas (DIG) or WIM (Warm Ionized Medium) as an important constituent of the ISM in the disk-halo interface has been recognized only more recently (Kulkarni and Heiles 1988, Reynolds 1990).

For the understanding of the complex interplay of the various phases of the ISM and star formation in galaxies, DIG plays an important rôle not only as the latest addition to the list of principal constituents of the ISM with filling factors of ~0.2 and up to 30% of the total atomic hydrogen content, but in particular also as a valuable diagnostic tool. Its existence and energy balance is closely related to the UV radiation field and radiative transfer in galactic disks, e.g., the question how leaky HII regions and how porous the ISM are. This specific question was addressed in several recent papers (Lehnert and Heckman 1994, Ferguson et al. 1996a, Hoopes at al. 1996) which all conclude

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that DIG contributes 25% – 50% of the Hα flux in spiral galaxies. In addition, DIG is an important tracer for halo components of the ISM in other galaxies since its emission line spectrum is rather easily accessible by optical imaging and spectroscopy. Most other tracers, such as radio continuum from cosmic rays or X-rays from hot plasma, either can not be observed with comparable angular resolution or sufficient sensitivity.

In the following, the known detections of extraplanar DIG in halos of galaxies are summarized, the current evidence for a correlation with star formation in the underlying disks and other components of gaseous halos is compiled, and the ionization problem for DIG is discussed. More detailed reviews of this topic can be found in, e. g., Dettmar (1992), Rand (1995), or Dahlem (1997).

2 Hα Imaging and Morphology of Extraplanar DIG

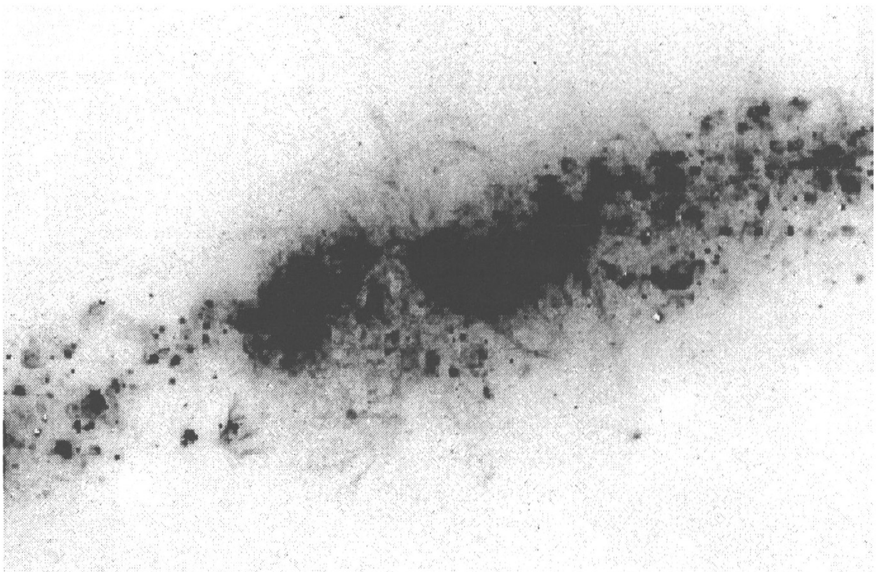

Fig. 1. Central part of the Sculptor group late type edge–on galaxy NGC 55 in Hα from Ferguson et al. (1996b)

The detection of a thick layer of DIG in NGC 891 which was found to be similar to the Reynolds layer of the Milky Way (Rand et al. 1990, Dettmar 1990) was followed by several Hα imaging searches. About two dozen 'normal' (i.e., excluding nuclear starbursts) edge-on galaxies have published results (Dettmar 1992, Rand et al. 1992, Pildis et al. 1994b, Rand 1996). Only few

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of them are showing evidence for a wide spread DIG in the halo comparable to NGC 891. In NGC 891 the DIG is distributed in long filaments (Rand et al. 1990, Dettmar 1990) and bubbles (Pildis et al. 1994a) of ionized gas embedded in a smooth background. In those objects showing Hα emission from the halo the spatial distribution is found to be very different, from thick layers with filaments and bubbles (e.g., NGC 4631, NGC 5775) to individual filaments and isolated plumes (e.g., UGC 12281). To demonstrate the complex morphologies of DIG two extreme cases are presented here.

NGC 55 is a late-type Sculptor Group galaxy with a very modest level of star formation. However, the energy released by starforming regions creates a spectacular distribution of the ionized gas (Fig. 1) with loops, bubbles, and long filaments extending far into the halo. The Hα image shows a clear difference in DIG morphology if regions of high star formation rate (SFR) are compared to quiet parts of the galaxy. The 'active' part shows (up to several hundred pc) long filaments as well as a smooth background of DIG. Some of the filaments can be traced back to individual HII regions in the disk. In the more quiet parts of the galaxy the DIG is confined to bubble like structures.

In the case of the prototype radio continuum- and X-ray halo galaxy NGC 4631 (Hummel and Dettmar 1990, Wang et al. 1995, Rand et al. 1992) the total far infrared (FIR) luminosity – 15 times higher than in NGC 55 (Rice et al. 1988) – indicates a high SFR. For this object Donahue et al. (1995) report the detection of a 30 kpc diameter halo of DIG down to an emission measure of 0.3 $cm^{-6}pc$. If confirmed, this very extended halo component of the ISM will be of interest for the discussion of gas halos in the early Universe.

With the latter example of NGC 4631 the key question with regard to the physics of DIG becomes obvious: what kind of source can supply the power required to keep the gas ionized. For the Milky Way DIG it was shown that only the UV radiation by OB stars meets the power requirements and that 10% – 20% of the UV photons have to leak out of HII regions (Reynolds 1990, 1997), a reasonable number if compared to the above mentioned results for other galaxies. However, even if the UV photons escape the HII regions, a special morphology of the ISM is still required to allow for the large free pathlengths that are needed to ionize gas several kpc out of the disk. With typical HI column densities of $N_{HI} \sim$several$\times 10^{20}$ cm^{-2} and an absorption cross-section of $\sigma = 6 \times 10^{-18}$ cm^{-2} near the Lyman edge, an ionizing photon could travel only very short distances if the extended HI layer would be distributed homogeneously. We will come back to the ionization problem in sect. 5 where the emission line spectra will be discussed. In the following we first address the relation of DIG to other phases of halo ISM.

3 Correlation with Other Gas Phases in the Halo ...

The best studied galaxies with respect to their halo ISM – and in particular their halo component of DIG – are the objects NGC 891 and NGC 4631.

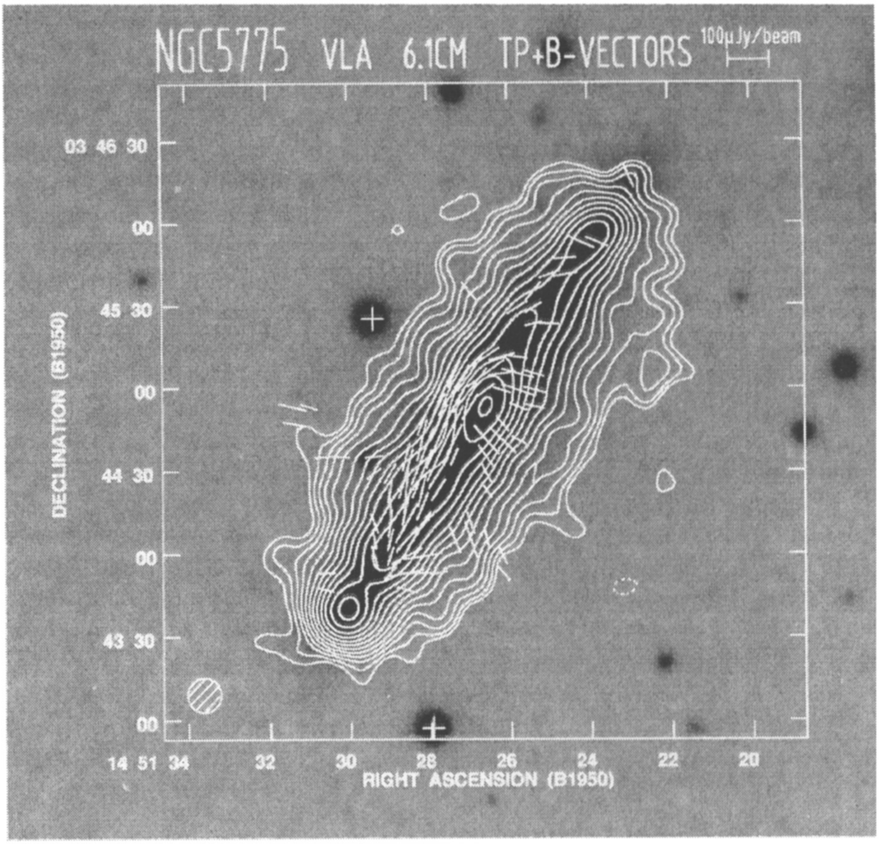

Fig. 2. The radio continuum halo of NGC 5775 at $\lambda 6$ cm obtained with the VLA at a resolution of 12″ (provided by G. Golla, unpublished). Vectors indicate the direction of the magnetic field as determined by linear polarization.

Both of them not only show prominent thick layers of DIG, they also possess extended radio continuum, H I, and X-ray halos. The spatial correlation of radio continuum emission, indicative of cosmic rays in a magnetic field found in a thick disk, and extraplanar DIG has been discussed for NGC 891 in detail (Dettmar 1992, Dahlem et al. 1994). It is shown there that the scale height for the ionized gas correlates with the scale height of cosmic rays. A particular active region 2′ NE of the nucleus not only shows individual filaments of ionized gas that can be traced out to 4–5 kpc above the disk, this region also shows H I emission high above the plane (see sect. 7). This H I gas could be comparable to Galactic High-Velocity Clouds. In addition, interferometer CO observations indicate a molecular spur reaching 520 pc above the plane in this region (Handa et al. 1992).

A search for more radio continuum halo or thick disk candidates by Hummel et al. (1991a) could identify only a few more suitable candidates for further studies of this suggestive correlation. One example is NGC 5775 (Fig. 2) which indeed also has an extended Hα halo. Again, radio continuum spurs are spatially correlated with Hα filaments (Dettmar 1992) and in the case of NGC 253 a possible correlation of such localized Hα filaments with radio continuum and X-ray spurs (Carilli et al. 1992, Pietsch 1994) is suggested by the comparison of these maps with a recent Hα image (Ehle, priv. comm.).

The radio continuum thick disks in some objects show rather high degrees of linear polarization (for a review see Beck 1997). In the case of NGC 891 (Hummel et al. 1991b) the highest degree of polarization is again observed above the most active part in the disk, the region 2′ NE of the nucleus (Hummel et al. 1991b, Dahlem et al. 1994). This is very surprising as one would expect the polarization here to be small due to Faraday depolarization by the thermal gas and part of the observed distribution of the polarized emission in NGC 891 must be influenced by Faraday depolarization along the different lines of sight. Although the halo of NGC 891 is missing a well ordered field on larger scales, a substantial ordered field has to be present locally and similar degrees of polarization (10%) are found in other radio continuum thick disks, too. Therefore magnetic field could be important for the physics of DIG.

Only for a few galaxies high resolution studies at various wavelengths are available to analyze such localized correlations. In particular we are still lacking FIR data that could be used for such comparisons; in this respect progress can soon be expected from ISO results. Although the examples above show that the presence of gas in galactic halos is in some cases a more localized phenomenon, evidence for the hypotheses that star formation activity in the disk is driving it can be found by comparing global properties.

4 ... and Star Formation in the Disk

To demonstrate this, we have compiled some properties of halo gas from the literature for all objects that have been searched for halo DIG. This includes a recently found new object, namely NGC 4634, with a very prominent and thick DIG layer with a FWHM of almost 500 pc (Fig. 3). Evidence for radio continuum or X-ray halo components is given together with a description of the DIG morphology. The thermal emission of dust in galaxies observable in the FIR is known to be a good tracer of star formation (e.g., Thronson and Telesco 1986) and therefore the SFR in the disk is characterized by the thermal IRAS FIR luminosity normalized to the optical diameter. Given the lack of angular resolution this results in a first order estimate for the energy input into the ISM per unit area.

FIR fluxes and the normalized FIR luminosities of these galaxies differ by almost two orders of magnitude and from this small sample the earlier

Tab. 1: DIG properties, SFR, and halo ISM

Object(Ref.)	$L_{FIR}/D_{25}^2 \times 10^{40\,(a)}$ (erg/s/kpc^2)	DIG distrib.&morphol.	radio halo	X-ray$^{(b)}$ halo
NGC 4666 (1)	14.5	bright, diffuse filaments	X	X
NGC 3079 (2,3)	8.9	bright, diffuse filaments	X	
NGC 5775 (4,5)	8.1	bright, diffuse+ filament	X	
NGC 253 (6-8)	8.1	bright, diffuse+ filamen	X	X
NGC 4634 (24)	5.9	very bright, extended		
NGC 3044 (5,9)	4.0	bright, diffuse	X	
NGC 4402 (26)	3.8	faint diffuse		
NGC 891 (10-13)	3.3	bright, diffuse+ filamen	X	X
Galaxy (14-16)	3.0	diffuse	X	X
NGC 4013 (5,9)	2.6	faint diffuse	?	
NGC 4631 (17-19)	1.8	bright diffuse	X	X
NGC 4302 (5,10,20)	<2.3	faint diffuse	?	
NGC 3432 (25)	1.6	?	X	
NGC 973 (5,20)	1.0	plumes	–	
NGC 55 (28,29)	0.9	giant filaments		?
UGC 3326 (5,20)	0.8	–	–	
NGC 5907 (9, 27, 30)	0.8	–	–	
UGC 12281 (20)	0.5	plumes		
UGC 2092 (5,20)	0.4	plumes	–	
UGC 10288 (5,9)	0.4	3 or 4 plumes	–	
NGC 4565 (10,21,30)	0.3	–	–	X
NGC 5746 (9)	0.2	–		
NGC 4244 (22,23)	<0.04	–	–	
NGC 5023 (9)	<0.09	1 or 2 plumes		
NGC 4217 (5,9)	<0.12	2 faint patches	X	
UGC 4278 (9)	<0.04	–		
NGC 4762 (9)	<0.15	–		

Notes: *(a)* distances from Tully 1988; FIR fluxes from Rice et al. 1988 or Fullmer and Lonsdale 1989; FIR for Galaxy from Cox and Mezger 1989. *(b)* only ROSAT detections are considered here.
(1) Dahlem et al. 1997 (2) Veilleux et al. 1995 (3) Duric et al. 1983 (4) Dettmar 1992 (5) Hummel et al. 1991a (6) Carilli et al. 1992 (7) Pietsch 1994 (8) Ehle (priv. comm.) (9) Rand 1996 (10) Rand et al. 1990 (11) Dettmar 1990 (12) Dahlem et al. 1994 (13) Bregman and Pildis 1994 (14) Reynolds 1990 (15) Beuermann et al. 1985 (16) Freyberg (1997) (17) Rand et al. 1992 (18) Hummel and Dettmar 1990 (19) Wang et al. 1995 (20) Pildis et al. 1994a (21) Sukumar and Allen 1991 (22) Walterbos 1991 (23) Schlickeiser et al. 1986 (24) this paper (25) English and Irwin 1997 (26) Dettmar 1995 (27) Dumke et al. 1995 (28) Ferguson et al. 1996b (29) Schlegel et al. 1997 (30) Vogler et al. 1996
– : non-detection
? : possible candidates that still lack confirmation or high resolution observations

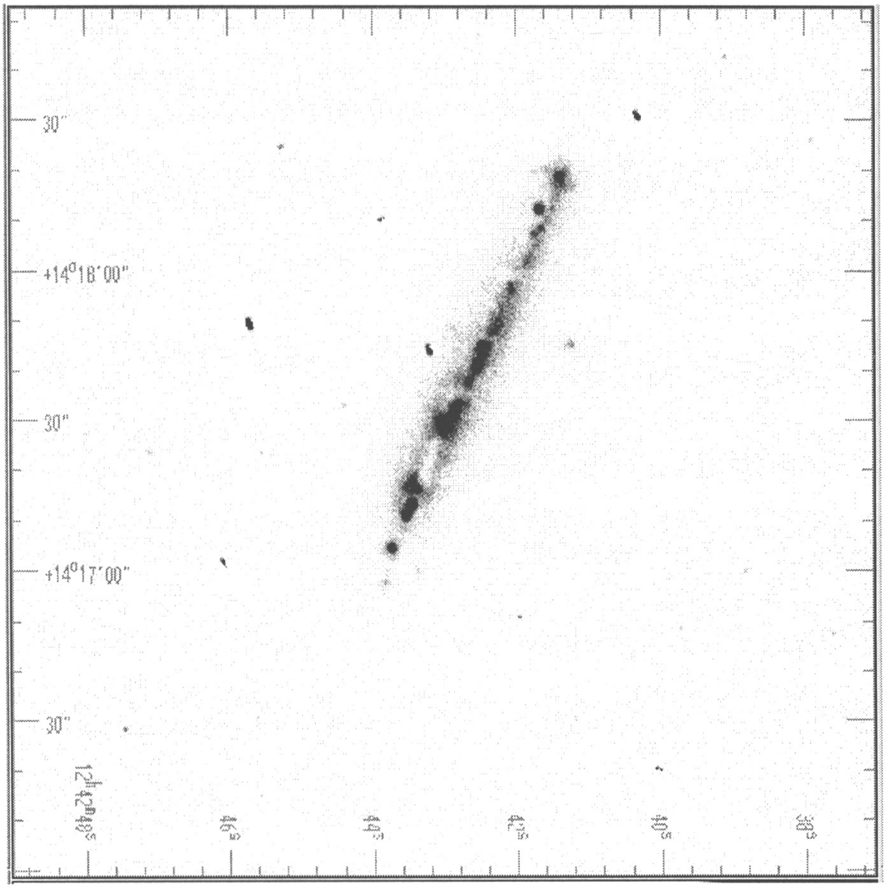

Fig. 3. Hα image of NGC 4634 obtained with the ESO/MPI 2.2 m telescope on La Silla using EFOSCII.

impression, that extraplanar DIG is related to star formation, emerges again. Bright and extended, widespread DIG layers as well as thick disks of radio continuum emission are found only in those objects with high SFR per unit area. In less active galaxies only individual plumes of DIG are found, which still could be caused by individual starforming regions. Only the observed X-ray halo in NGC 4565 and the radio data for NGC 4217 do not fit into a scenario that relates extraplanar DIG, radio, and X-ray halos to the SFR in the disk. It is worth mentioning that the Milky Way actually fits into this picture, details are described in Dettmar (1992). One should keep in mind that the compilation in Tab. 1 is still based on very inhomogeneous data, in particular with regard to sample selection and detection limits, and that it is therefore difficult to perform a more quantitative analyses.

5 Ionization of DIG

As it was mentioned in Sect. 2, the most important question for our understanding of DIG is that for the ionizing process. The papers by Miller and Cox (1993) and Dove and Shull (1994) show, that the thickness of the ionized layer can indeed be attributed to the UV radiation field caused by a typical distribution of OB stars in disks of spiral galaxies.

However, the detailed information on the ionization and excitation conditions from long-slit emission line spectroscopy is not that easily explained by photoionization models. Spectroscopic observations of extraplanar DIG are now available for NGC 891 (Dettmar and Schulz 1992, Rand 1997), NGC 4631 (Golla et al. 1996), NGC 2188 (Domgörgen and Dettmar 1997), and NGC 55 (Ferguson et al. 1996b). Generally the observed line ratios of [NII]/Hα and [SII]/Hα vary with distance from the plane. Both, [NII] and [SII] lines, are becoming relatively stronger at higher z and ratios up to [SII]/H$\alpha = 0.6$ and [NII]/H$\alpha = 1.4$ are observed. As a typical example the line ratios along a slit parallel to the minor axis of NGC 4631 are given in Fig. 4.

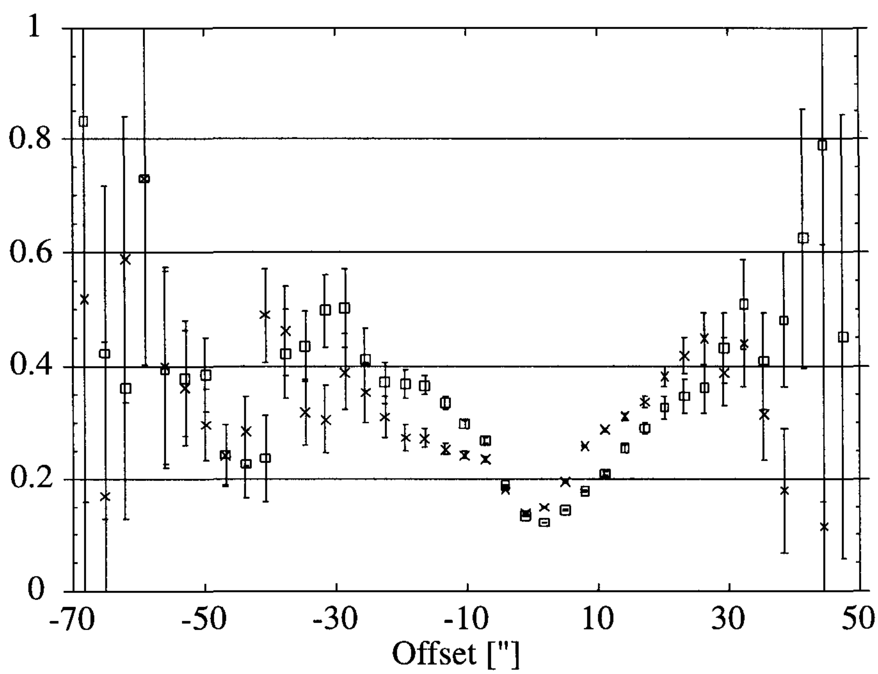

Fig. 4. Variation of emission line ratios [NII]/Hα (□) and [SII]/Hα (x) as a function of distance above the galactic plane in NGC 4631 (from Golla et al. 1996)

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To explain the relatively strong [NII] and [SII] lines together with the weak [OI]λ6300 Å and [OIII]λ5007 Å lines observed in the Reynolds-layer of the Galaxy the radiation transfer for photoionization models in a low density regime (Mathis 1986) was modified to account for these observations (Domgörgen and Mathis 1994). Since these models require a certain hardness of the radiation field a prediction was made for the expected fraction of ionized He. The reported upper limit for the HeI λ5876 Å line along two lines of sight in the Reynolds-layer (Reynolds and Tufte 1995), however, is inconsistent with the model predictions. The upper limit corresponds to an ionized fraction of helium relative to hydrogen $\chi_{He}/\chi_{H} \lesssim 0.25$ and such a small fraction of ionized He in the Milky Way is supported by radio-recombination-line observations of Galactic DIG filaments ("worms") by Heiles et al. (1996) with even stricter limits on χ_{He}/χ_{H}.

With regard to He^{+} the extragalactic situation is slightly different since Rand (1997) presents a very deep spectrum of NGC 891 with the detection of HeI λ5876 Å in the DIG. From this observation one can conclude that the ionizing radiation field is significantly harder than in the Reynolds-layer. However, in NGC 891 the line ratio for [NII]/Hα reaches 1.4, a value that is still not explainable with the radiation field deduced from the HeI/Hα ratio. To account for this enhanced, low-ionization emission there is still additional heating required.

It is possible that shocks may contribute at higher z and some indication for such effects are given by Dahlem et al. (1997). Additional contributions could come from photoelectric heating by dust (e.g., Reynolds and Cox 1992), and a lack of coolants due to metal depletion, or, of course, a combination of these effects. The Decaying Dark Matter theory, in which the decay of a 27eV neutrino produces ionizing UV photons, was for example applied to the DIG in NGC 891, too (Sciama and Salucci 1991). A completely different approach to the ionization problem is attempted by models that try to explain the DIG as the cooling phase of a galactic fountain phenomenon. In this context mixing, heat conduction, and non-equilibrium processes might be important (e.g., Breitschwerdt 1997, Slavin et al. 1993, Shapiro and Benjamin 1993). This discussion makes clear that the heating and ionization of DIG is still not well understood and several contributions at this conference address the question of additional sources of energy such as magnetic reconnection (Birk and Lesch 1997) or by turbulence (Minter and Balser 1997).

6 Dust (Mixed in)

All the various phases of the ISM come with some "contamination" by dust and from theoretical arguments dust is expected to be present in the halo too, driven out either by coupling to the gas "blow out" or by radiation pressure (Ferrara 1997). Indeed, in many edge-on galaxies filaments of dust perpendicular to the disk or giant loops of dust reaching into the halo can be identified (Keppel et al. 1990, Sofue et al. 1995). Sofue et al. suggest, that the dusty loop structures and filaments observed in NGC 253 are influenced by magnetic fields. This dust can be important for the physics of halo gas, e.g., since it may contribute to the energy balance by photoelectric heating (Reynolds and Cox 1992) or radiative losses due to fast spinning small grains (Ferrara and Dettmar 1994). It could also influence the emission line diagnostics of the disk since its scattering properties will change the observed line ratios (Ferrara et al. 1996).

7 Velocity Information

If DIG (and other components of the ISM) in the halo are due to dynamical processes, important information on its origin and ionization could come from kinematical studies. This source of information has not been much used yet, mainly for sensitivity reasons. In the case of NGC 891, however, there is evidence for peculiar velocities of DIG (Pildis et al. 1994a, Rand 1997) and HI (Swaters et al. 1996). For both components a deviation from corotation is observed on scales of 2 kpc above the disk in the sense that the halo gas is rotating slower as it is expected in "fountain flow" models in which uprising gas is moving outwards (Bregman 1980).

8 Conclusions

DIG is an important tracer for gas in halos of galaxies and its emission line spectrum offers several important diagnostic tools, such as kinematic information, whose possibilities have not yet been fully explored. The evidence for a correlation of extraplanar DIG with other phases of gas in galactic halos and with the SFR in the underlying disk is supporting models that describe a large scale circulation of matter between actively starforming regions in the disk and the halo such as *galactic fountains* (Shapiro and Field 1976, Kahn 1997), *chimneys* and *superbubble blow outs* (Norman and Ikeuchi 1989, Mac Low et al 1989., Mac Low and Ferrara 1997), or *winds* (Habe and Ikeuchi 1980). However, details of the processes and the importance of specific models remain still unclear and the uncertainties with regard to the ionization and excitation of DIG reflect this situation.

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