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The warm ionized gas in galaxies

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Abstract

In this review a few topics of the ionized gas in galaxies with direct relevance to the conference are touched. After some comments about the structures in the interstellar medium and their possible ionization mechanisms, I discuss the recent progress with stellar atmospheres and therefore Lyman continuum fluxes of hot stars. Based on the improved ionizing radiation fluxes I touch on the problems of ionization and the line ratios observed in both the diffuse ionized medium in the disks and the halos of star forming disk galaxies. The size on the ionized gas halos and the link to the ionized gas in the large scale structure are also discussed.

1 Structures in the ionized gas

Several good reviews on the physics of the warm phase of the interstellar medium are in the literature, but most are either concentrating on the theoretical background, or concentrate on one or few of the mayor constituents, like H II regions, the diffuse ionized medium, or shell structures. Here I like to take an observers view and grab a few key points, where changes in our understanding have been/are taking place in recent years.

The warm ionized gas in galaxies comes in very different structures, which reflect their creation mechanisms and their ionization sources. While the ionization source of some of the object classes are clear and very detailed analyses can be made like for classical H II regions, the physical nature of other object classes are much less clear. The small compilation of Tab.1 shows that especially at the large scales the relative contributions of photo- and shock-ionization for creation and maintenance of the ionized gas is quite unclear. It appears that with increasingly larger spatial scales many different objects (and processes) can contribute significantly.

It is important to sort out the sometimes quite inconsistent definitions about shell structures in the ISM. Here we refer to circumstellar shells as the following: shells around single stars are bubbles (circumstellar, if they contain CNO processed material; interstellar, if they consists mainly of compressed interstellar material), shells around OB associations are superbubbles, shells around stellar complexes or sets of stellar associations are supergiant shells, following the nomenclature of Chu (1995). This immediately implies a size order, which is well visible in Fig. 1. Circumstellar bubbles have diameter from 1 to about 30 pc, superbubbles around 100-200 pc, supergiant shells show diameters of 1 kpc. The supergiant shell LMC 4, which is shown in the diagram has even an diameter of 1.4 kpc. Obviously the size is not only depending on the energy input, and age, but also on the surrounding density. In M 33 two interstellar bubbles are known with diameters of 100 pc (Oey & Massey 1994).

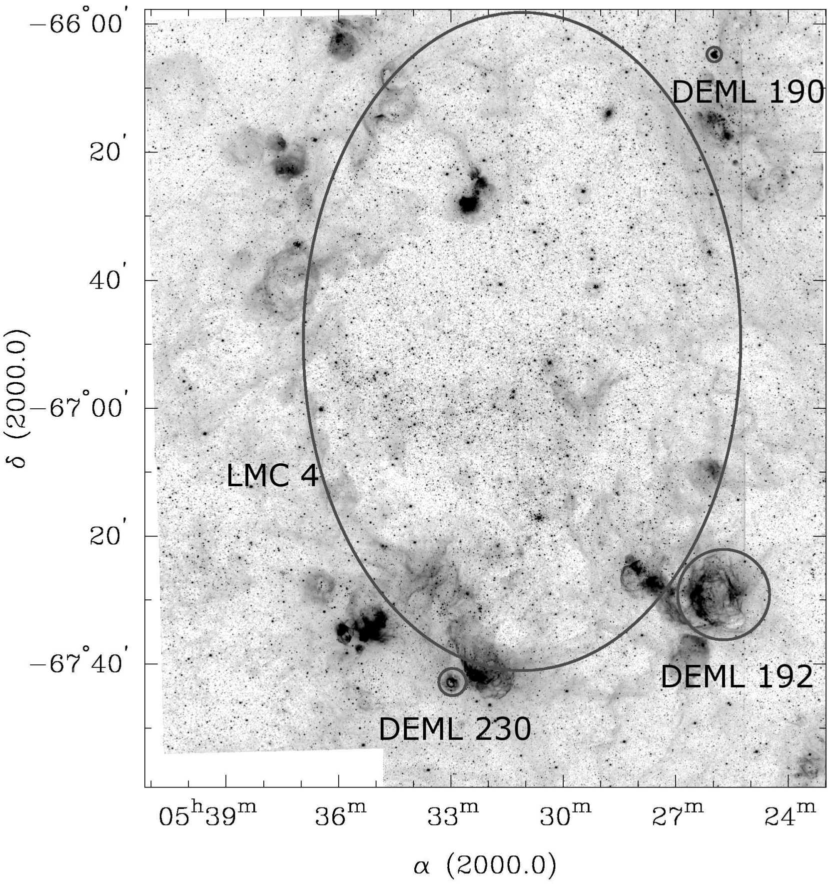

Figure 1: Hα image showing the size scaling of interstellar bubbles. The field contains the supergiant shell LMC 4 with a diameter of 1.4 kpc. The supergiant shell, the superbubble DEM L 192 (diameter 100 pc), the interstellar bubble DEM L 230 (diameter 10 pc), and the supernova remnant DEM L 190 (diameter $\sim$ 2 pc) are marked.

2 Ionization of diffuse medium

With the deep Hα plate of the LMC (Davies et al. 1976) and the Fabry-Perot observations (Reynolds 1980) a diffuse ionized gas (DIG) became obvious both in the disks of starforming galaxies and in the halo of our galaxy and later in other galaxies (e.g. Dettmar 1990). The ionization mechanism was (and still is) not fully clear. Still, simple energy estimates showed that the leaking of Lyman continuum photons out of classical H II regions must be a dominant source of ionization, especially in the disk. The contribution of this diffuse gas to the total Hα flux of a galaxy can be more than 40% (e.g. Kennicutt et al. 1995). The large extent of this diffuse medium can be well seen in the LMC (Fig.2). This Hα image also shows the different morphologies of the DIG (from shells and filaments to truly diffuse structures). Still the inclination of the LMC prevents an easy estimate how much of the DIG is located at large distances from the plane of this galaxy.

structure	spatial	process	ionizing source
H II regions	localized	photo-io.	stars
Planetary Nebula	localized	photo-io.	stars
Supernova remnants	localized	shock-io.	explosion
Circumstellar bubbles	localized	photo-io.	stars, stellar winds
Superbubbles	localized	both	stars, X-ray
AGN cores	localized	photo-io.	powerlaw continuum
disk gas	diffuse	both	stars, winds, SN shocks
AGN ionization cones	both	both?	powerlaw, outflows?
halo gas	diffuse	both?	stars, outflows, SN Ia
intergroup medium	diffuse	both?	outflows, background?
intergalactic medium	diffuse	both?	background, shocks?

Table 1: The table list the most important structures of the ionized interstellar medium, their spatial structures, the ionization process, and the objects responsible for ionization.

The recent years saw significant changes of the understanding of stellar atmospheres. The new line-blanketed NLTE models with inclusion of stellar winds (CMFGEN (Hillier & Lanz 2001), WMBASIC (Pauldrach et al. 2001)) lead not only to a much better reproduction of the observed stellar spectra, but gave also a new effective temperature scale for hot stars (Martins et al. 2002; Smith et al. 2003). With the better treatment of the line blanketing the far UV fluxes of the stars changed significantly. This obviously has also effects on the ionization of the gas. In the diffuse ionized gas (DIG) several diagnostic line ratios were for a long time hard to reproduce with photoionization models. This problem is very obvious in the WHAM survey (Reynolds et al. 1998) of the galactic ionized gas (Reynolds et al. 2004) and in the DIG observed in several other galaxies (e.g. Tüllmann & Dettmar 2000). This lead Haffner et al. (1999) to the suggestion of an additional heating source of the DIG. New photo-ionization calculations using the NLTE stellar atmospheres seem to able to reproduce e.g. the [N II]/[S II] ratio without additional physics (Elwert et al., in prep.). Still, not all the problems of the ionization of the DIG can be solved this way. The rising [O III]/Hα with z-distance from the plane e.g. in NGC 5775 (Tüllmann et al. 2000; Rand 2000) may need additional physics, as do some other line ratios, but this leads to the diffuse gas in the halo of starforming disk galaxies.

3 Ionized gas outside the disks

The detection of DIG in the halo of spiral galaxies made the problem of the ionization mechanism even worse, since one needs to postulate an interstellar medium topology to allow the Lyman continuum photons to escape to large distances from the sites of starformation. The idea of the Chimney model (Norman & Ikeuchi 1989) seemed to be an attractive direction, but only few of the low density tunnels through the ISM have been found up to now (Normandeau et al. 1996). Indeed, local galaxies seem to loose relatively few Lyman continuum photons (Heckman et al. 2001), while the situation may be completely different at high redshift. The link between high starformation and a DIG halo seems to be well established by now (Lehnert & Heckman 1996; Rossa & Dettmar 2003a,b), but the explanation of the line ratios (Miller & Veilleux 2003), as mentioned already before, may require more that the

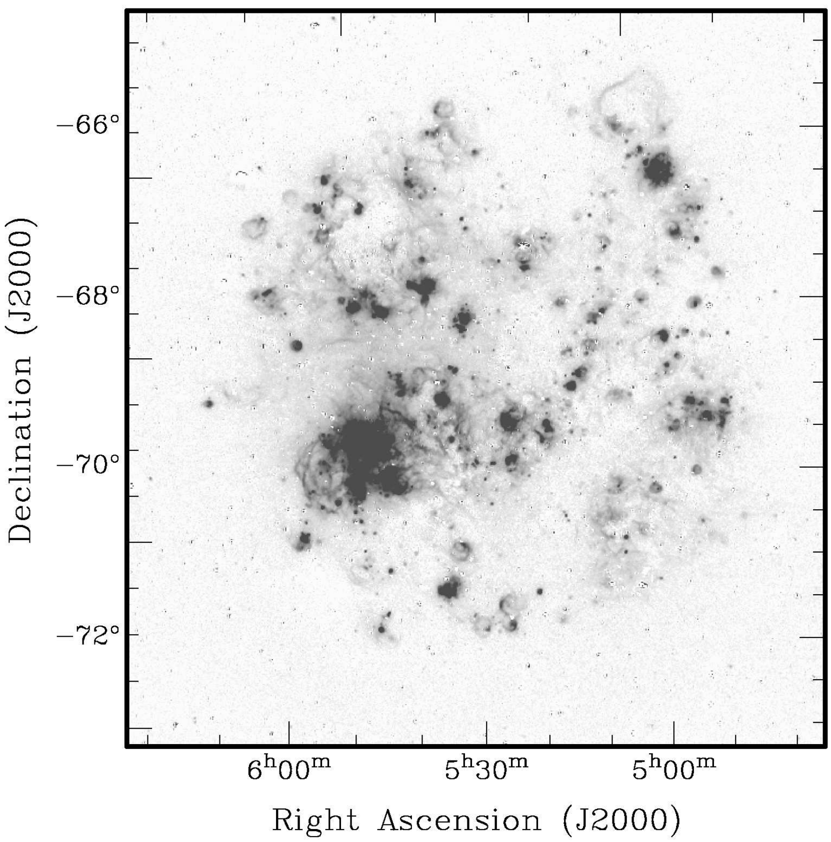

Figure 2: Continuum corrected Hα image of the LMC based on data from the SHASSA database (Gaustad et al. 2001). Besides the giant H II region 30 Dor and the many other H II regions of the LMC, shells and large filaments of the DIG, as well as a diffuse, structureless DIG are visible. Note the large areas diffuse warm ionized medium at large distances from bright H II regions and between the giant H II region 30 Dor and the supergiant shell LMC 4.

normal photoionization modeling.

There is nevertheless an important distinction to make. In nuclear starburst galaxies the spatially confined high starformation region in the galaxy center leads to well defined outflow cones, beautifully displayed in e.g. M 82. A high level of starformation in large regions of the disk lead naturely to an extended DIG in the halo. The nearby galaxy NGC 253 is a very good example for this case, see Fig. 3. The B-band image shows complex dust filaments indicative of gas driven out of the plane by the many star forming regions, and not the nuclear region alone. The continuum corrected Hα image shows the strong starformation in the disk and several large spurs of ionized gas out into the halo. This ionized gas correlates well with the diffuse X-ray emission in the halo of NGC 253 (Pietsch et al. 2001;Strickland et al. 2002) and the polarized radio continuum emission (see e.g. Heesen et al., this meeting). NGC 253 is also an nuclear starburst galaxy, but the outflow cone of this strong starformation event in the core of the galaxy is at much smaller scale (yet) (e.g. Weaver et al. 2002) than the kpc-sized Hα and soft X-ray structures. The link between large DIG spurs and polarized radio continuum spurs is visible in several such galaxies (see Tüllmann et al. 2000). The magnetic field vectors run parallel along the spurs contrary to the mostly parallel magnetic field in the disk, hinting at a close connection between DIG spurs, starformation, and large-scale magnetic field topology in such galaxies.

With structures of that size, timing become an interesting topic. It appears that the largest shells in dwarf galaxies are to large (and to slowly expanding) to be created by the kinetic energy input of the currently observed generation of star (van Eymeren et al. 2005). Similar arguments can be used here. The size of the Hα streamers present in the halo of NGC 253 (Fig. 3) imply that not the current starformation event of the disk is the source of this gas, but a similar event about 10^8 years ago. It is important to note that the X-ray emission seem to be located at the inside of the Hα filaments (Cecil et al. 2002). This implies a close link between the diffuse Hα emission and the hot gas. The analysis of the properties of this ionized gas is especially difficult with the possible contributions to the ionization and heating from photoionization from the soft X-ray photon, turbulent mixing layers, and thermal conduction between the hot and warm gas.

The full inventory of the ionizing sources for the halo emission is a critical point. In the last years several cases for H II regions in the halo of disk galaxies were detected (e.g. Tüllmann et al. 2003). They show, that in addition to the ionizing sources in the disk and the extragalactic background, some contributions of sources in situ can play a role. In addition to young, massive stars in the halo, there are UV-bright, evolved, low-mass stars (post-asymptotic giant branch stars, extended horizontal branch stars, and white dwarfs), or shock ionization from supernovae of type Ia (e.g. Shelton 2000). Another point worth mentioning is the idea, that current photo-ionization codes are not fully appropriate for the problem. If most of the disk is the source of the Lyman-continuum photons (or many low density channels into the halo), geometric effects may be important for the ionization pattern of the halo gas. Photo-ionization Monte-Carlo codes (Tüllmann 2002; Wood & Mathis 2004) may be necessary to model the conditions of the gas in the halo of starforming galaxies.

4 Intergalactic medium

Going to even larger scale, we come into the regime of intragroup medium and the intergalactic medium. Absorption lines against background sources at higher redshift are the most widely used methods to study the intergalactic medium. The low densities of the gas, and the observational problems (large fields of view, stray light from bright sources) make the detection of emission lines of the ionized intergalactic medium very hard. The gas has to be ionized to a quite high degree due to the presence of the UV and X-ray background radiation. In a few cases the outer regions of galactic disks, where the transition from mainly neutral to mainly ionized has happened, where successfully observed (Bland-Hawthorn et al. 1997).

When the DIG halo reaches about 100 kpc radius around a galaxy, it starts to have significant implications for the interpretation of quasar absorption lines. Detection of $H_{Ly\alpha}$ lines with very similar velocities of foreground galaxies but spatial distances of more than 100 kpc (e.g. Côté et al. 2005) show the presence of gas at such large distances. Still, a detailed analysis of the velocities show that we may start to leave the regime of individual halos and detect gas inside the large scale structure.

One experiment to determine the size of warm ionized gas halos yielded a detection of a very large halo around the galaxy NGC 4631 (Donahue et al. 1995). The halo may also de-

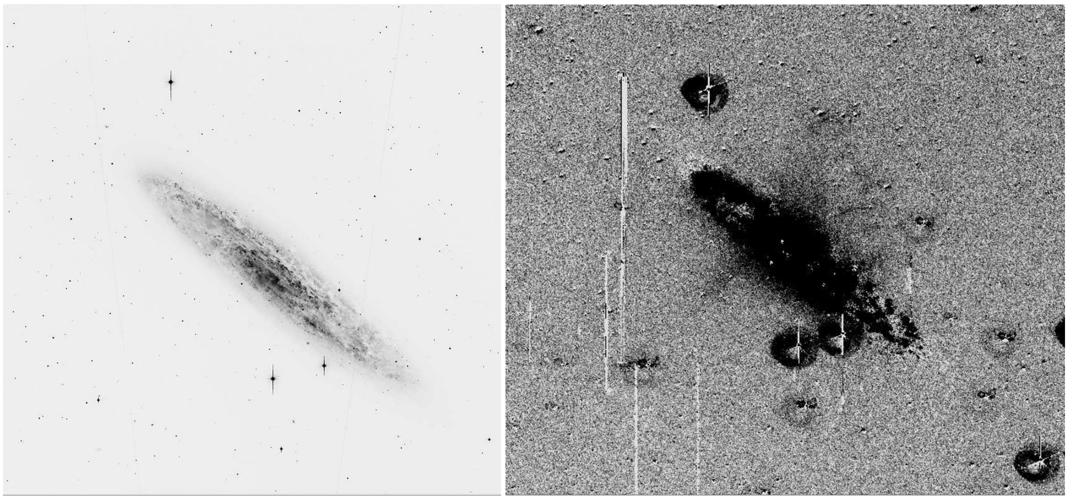

Figure 3: Two images of the starburst galaxy NGC 253; left: B-band image showing actively star forming disk and complex dust structures apparently driven our of plane of the galaxy; right: continuum corrected Hα image with several kpc-sized ionized gas spurs emanating far into the halo.

scribed as halo plus bridge to the neighboring galaxy NGC 4656. While tidal interaction may well play a role here as indicated by the HI structure (Rand 1994), the observation of this Hα halo still gives a very useful measurement of a maximum scale. Unfortunately, this critical observation was not repeated yet. With tunable filters even deeper observations may be possible (Bland-Hawthorn et al. 2001), approaching the sensitivity needed to detect the ionized gas predicted to exist in the filaments of the large scale structure (e.g. Davé et al. 2001). Recently, a detection of large filament between M 31 and M 33 in 21cm emission was reported (Braun & Thilker 2004). If true, a counterpart of this gas should be relatively easy to detect in e.g. Hα, since the ionization fraction of this gas must be high, except if it consists only of very dense, small clumps.

5 Conclusions

Clearly, we are in a time of large progress in the observing and explaning of the ionized medium in and around galaxies. Still, several problems concerning the ionization, structure and extend of this gas are not fully solved yet. These problems have potentially large implicatons for our understanding of the UV background, the local baryon content of the universe, and the processes of galaxy formation and evolution.

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