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The Coronal Gas Phase of the ISM

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Abstract

Diffuse thermal X-ray emission due to the hot gas component of the ISM is seen not only in the disks but also up to large distances above the planes of edge-on starburst galaxies. These outflows do not only have an influence on the evolution of the galaxy but are potentially significant also in enriching and heating of the intergalactic medium.

A widely accepted model is that supernovae (and stellar winds) in the disks of star-forming galaxies create, via blow-out and venting of hot gas, a tenuous hot extraplanar ISM gas component. The soft thermal X-ray emission observed is either this metal-enriched preexisting halo medium, which has been swept up and shock-heated by the starburst driven wind, or wind material compressed near the walls of the outflow by reverse shocks within the wind.

Observations of starburst galaxies with the current generation of X-ray telescopes (XMM-Newton and Chandra) are demonstrating that the soft thermal X-ray halo emission is highly structured and spatially correlated with Hα emission, as expected in case of an interaction of the galactic wind with a cooler ambient medium.

The role of the halo magnetic field configuration in the dynamics of the hot X-ray emitting gas has not yet been addressed in detail but a correlation of X-ray halo features and vertical magnetic field lines might exist.

1 Introduction

The existence of thermal X-ray emission from hot plasmas with temperatures above a million Kelvin has been demonstrated during the last decades by observations obtained from a sequence of X-ray space missions with ever increasing sensitivity, spectral and spatial resolution. Such X-ray emission signatures have been found in a large variety of cosmic sources including optically thin sources like solar and stellar coronae, supernova remnants, the interstellar and even intergalactic space. At higher densities accretion powered objects like X-ray binaries and active galactic nuclei, where a central X-ray emitting region is partially photoionizing a surrounding cooler medium, also emit thermal X-ray emission - a discussion of such dense plasmas which are described by the so called 'nebular' and 'atmosphere' thermal model, however, would be beyond the scope of this paper.

2 Radiation Processes

Usually the two most important radiation processes in optically thin plasmas are:

- bremsstrahlung continuum emission produced by a transition of a free plasma electron between two continuum states above the ionization limit of the ion: the energy spectrum is $\propto T^{-1/2}e^{-E/kT}$ and dominates at $T \gtrsim 10^8$ K.

- discrete line emission, i.e. electronic transition between two bound levels of the ion, dominant at $T \lesssim 5\,10^7$ K. Such lines from highly ionized atoms are clear signatures of the thermal nature of hot plasmas.

Less important processes are radiative recombination continuum (capture of an electron into a bound state of the ion), dielectronic recombination lines (capture of a free electron into a doubly excited ion state through simultaneous excitation of a bound electron of the ion), and two-photon continuum (simultaneous emission of two photons from a metastable state).

For full details on the X-ray emission processes and spectroscopy of the hot gas in the ISM the reader is referred to the book by van Paradijs & Bleeker (1999).

2.1 The Coronal Model

Model assumptions are needed to derive from observations the relevant astrophysical parameters like electron temperature, volume density and elemental abundances. Since the discovery of X-rays from the sun in 1948, the thermal standard model for optically thin sources has been applied to the solar corona (pioneering work by Elwert 1952) and is therefore named the 'coronal' model. Since then the new series of X-ray satellites has put strong demands on the availability of spectral codes with higher accuracy and more details. Spectral models to explain the observed X-ray emission from coronal plasmas have been developed for example by Raymond & Smith (1977) (RASM; see Fig. 1; Mewe & Gronenschild 1981; Landini & Monsignori Fossi 1990). The coronal model assumes that the plasma is optically thin, of such

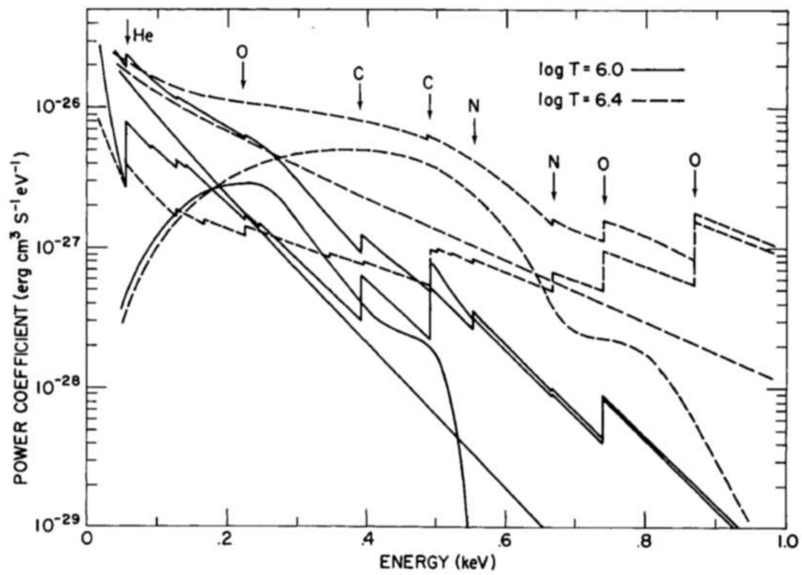

Figure 1: Continuum X-ray and EUV spectra as derived from the RASM model: Three types of continua are included, bremsstrahlung (smooth monotonic curve), radiative recombination (curve with edges or steps), and two-photon continuum (curve with rounded humps). For the two shown temperatures, the uppermost curve is the sum of the three continua (Fig. 2 of Raymond & Smith 1977)

low density that the excited state populations are negligible to the ground state population, that radiative losses are balanced by non-radiative (mechanical) heating, and that plasma electrons and ions are relaxed to Maxwellian energy distributions with a common temperature, T, a free parameter controlled by external processes. If the coronal gas is in a stationary ionization state where the collisional ionization rate is balanced by the recombination rate (which requires three-body collisions - one electron recombining with an ion, another one carrying away the excess energy) it is said to be in 'collisional ionization equilibrium' (CIE).

3 Coronal Gas in Galactic Halos

Though detailed theoretical arguments are lacking, it seems not unlikely that the hot gas rising in superbubbles may provide a substantial source of thermal energy to the halo and thus maintain a more extensive coronal gas at high temperature. While the existence of a widespread hot gas in the galactic disk is conclusively established by measures of O VI absorption and soft X-ray emission, the presence of a similar hot gas at kiloparsec distances from the galactic plane was for a longer time less certain. The study of the coronal gas phase in galactic halos is of special importance as this component of the ISM is believed to consist of metal-enriched ejecta of supernova remnants, driven out of the disk by buoyancy, and as such is a direct tracer of the chemical enrichment of the disk ISM and of the galactic chemical evolution. The detection of such a coronal gas in halos would also demonstrate that the metal re-distribution is not only taking place in galactic disks: hot gas could rise and fall back to the disk plane far away from its creation side (if halos are indeed not co-rotating). Furthermore, galactic halos might even have an impact on the enrichment of the intergalactic medium. The probably best studied and most common form of galactic outflow polluting the intergalactic medium are superwinds (Heckman et al. 1990; Dahlem 1997).

3.1 Dynamical Models

Since the introduction of the theory by McKee & Ostriker (1977) on the three component ISM, postulating that a large fraction of the volume of the ISM in the disk of the galaxy is filled with hot, tenuous gas, it has become increasingly clear that supernova explosions do not only alter the cool cloud structure of the disk medium but also influence the gaseous galactic halo. McKee & Ostriker (1977) already speculated about the existence of hot gas in galactic halos which (at a temperature of 10^6 K) would have a density of $\sim 5\,10^{-4}$ cm^{-3} and as such should be detectable in X-rays.

The disk-halo interaction was further investigated by Norman & Ikeuchi (1989) who studied superbubbles (generated by spatially and temporally correlated type II supernovae) that break out of the galactic disks and form collimated structures. These so called 'chimneys' enable an upward flow of mass, energy, momentum, and magnetic flux and (after cooling) a downward flow from the halo to the disk. The essential difference to the McKee & Ostriker model is the prediction that the filling factor of the hot gas in the disk should be significantly less than unity.

Strickland & Stevens (2000) used a hydrodynamical CIE model to simulate starburst driven galactic winds with the aim of studying how the wind dynamics, morphology and X-ray emission depend on the ISM distribution of the host galaxy, the starburst star formation history and its strength. Figure 2 (extracted from Strickland & Stevens 2000) shows the distribution of the wind number density resulting from a thick- and thin-disk model. Whereas

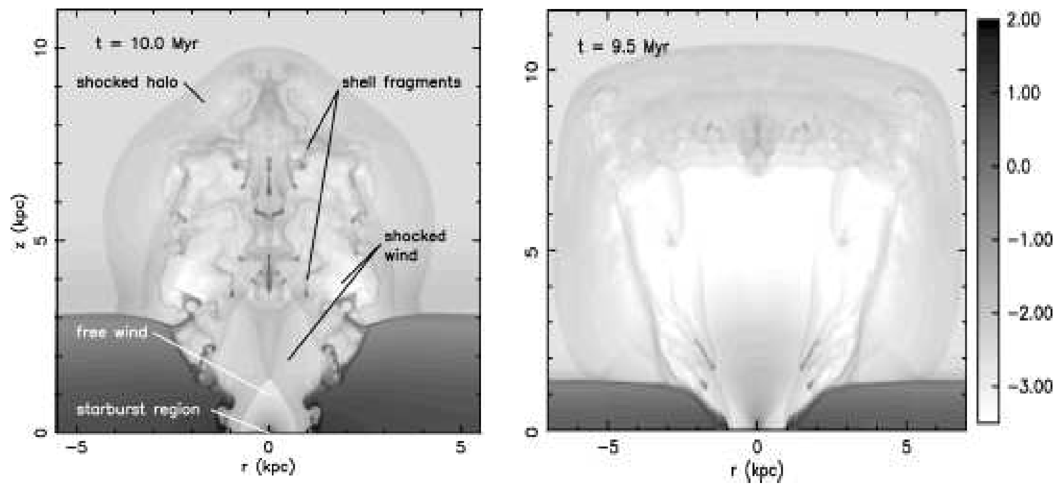

Figure 2: Results of the CIE starburst driven wind model: logarithm of the wind number density for a thick-disk (left) and thin-disk (right panel) model after 10 and 9.5 Myr simulated evolutionary time (from Figs. 4 and 6 of Strickland & Stevens 2000)

in the thick-disk model the outflow is strongly collimated and complex, in the thin-disk model - corresponding to a deeper gravitational potential of the galaxy - the resulting number densities are significantly lower.

Such simulations support the expectation that X-ray emission from galactic winds originates from a complex phase-continuum of gas, covering a wide range of different temperatures and densities, in contrast to the commonly made assumption of a distinct gas phase when fitting simple spectral model to observed X-ray spectra of the coronal gas. Other important findings of these simulations are: the soft X-ray emission in galactic winds possibly originates from a low filling factor ($\lesssim 2$ %) gas which carries only a small fraction of the mass and energy of the wind. The majority of the thermal and kinetic energy of these winds is in a volume-filling hot ($T \sim 10^7$ K) component, which is extremely difficult to observe because of its low density and resulting low emissivity. Starburst driven winds seem to be a good mechanism for the re-heating of inter galactic and even inter cluster medium.

An important further development of the galactic outflow model was initiated by the work of Breitschwerdt & Schmutzler (1999, also see Breitschwerdt 2003), showing in detail how a fast adiabatically expanding plasma and the resulting non-equilibrium distribution of the highly ionized species evolve in a galactic wind. In this model (see Fig. 3) the wind is mainly driven by thermal pressure but also is assisted by cosmic rays and MHD waves. The CIE assumption is considered as being valid only as approximation during limited periods. Instead, the non-equilibrium ionization (NIE) is modeled taking into account the feedback between the dynamics of the plasma and its thermal evolution: the dynamics changes the gas density and pressure and hence the ionization structure. This leads to changes in the radiative energy losses which then again influence the gas dynamics, etc. In particular, the X-ray emission spectra obtained from such non-equilibrium simulation are found to be radically different from CIE assuming models.

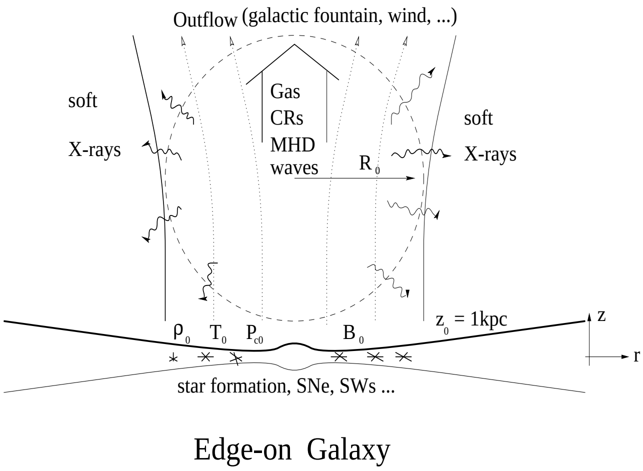

Figure 3: Sketch of the non-equilibrium galactic outflow model (Fig.6 of Breitschwerdt 2003)

3.2 X-ray observations

The observation of soft extended X-ray emission from the coronal gas phase is a powerful tool to trace the distribution of this hot gas (via spatial analysis) in the galactic disks and halos, and (via X-ray spectroscopy) to derive the gas temperature and chemical composition and to test model assumptions (like CIE or NIE). If reasonable assumptions about the emitting volume can be made, it is even possible to derive estimates about the gas density, mass, cooling time and thermal energy density (see Ehle et al. 1998, Ehle 2005 and references therein).

An impressive catalog of high resolution Chandra (Weisskopf et al. (2002)) X-ray (and ground-based optical Hα) imaging of edge-on star forming disks covering the full range of star formation intensity in disk galaxies was presented by Strickland et al. (2004a, 2004b). The Chandra X-ray spectra of extraplanar emission from all these galaxies can be fitted with a common two-temperature MEKAL (Mewe, Kaastra & Liedahl 1995) spectral model ($kT \sim 0.1$ keV and ~ 0.4 keV) with metal abundances showing supersolar ratios of α-process elements (primarily oxygen) to iron. This is consistent with the origin of the X-ray emission being either (metal enriched) merged supernova ejecta or from shocked ambient halo ISM.

Whereas Chandra's unequaled spatial resolution allows the robust detection and removal of point sources (entangled with the diffuse emission due to hot gas), XMM-Newton (Jansen et al. (2001)) offers unprecedented sensitivity for the low surface brightness extended emission allowing detailed studies of spectral variations of the diffuse X-ray emission in the disk and halo. This has impressively been demonstrated for example in the analysis of observations of the prototypical starburst galaxies M82 (Stevens et al. 2003) and NGC 253 (Pietsch et al. 2001).

3.2.1 Our project: Dependence of galactic halos on star formation activity in the underlying disks

In a collaboration (mainly with M. Dahlem, ATNF) we have selected nearby edge-on oriented starburst galaxies to perform a multi-wavelength (X-ray, radio-continuum, HI and optical) study of all phases of extraplanar gas to investigate the dependence of galactic halo properties

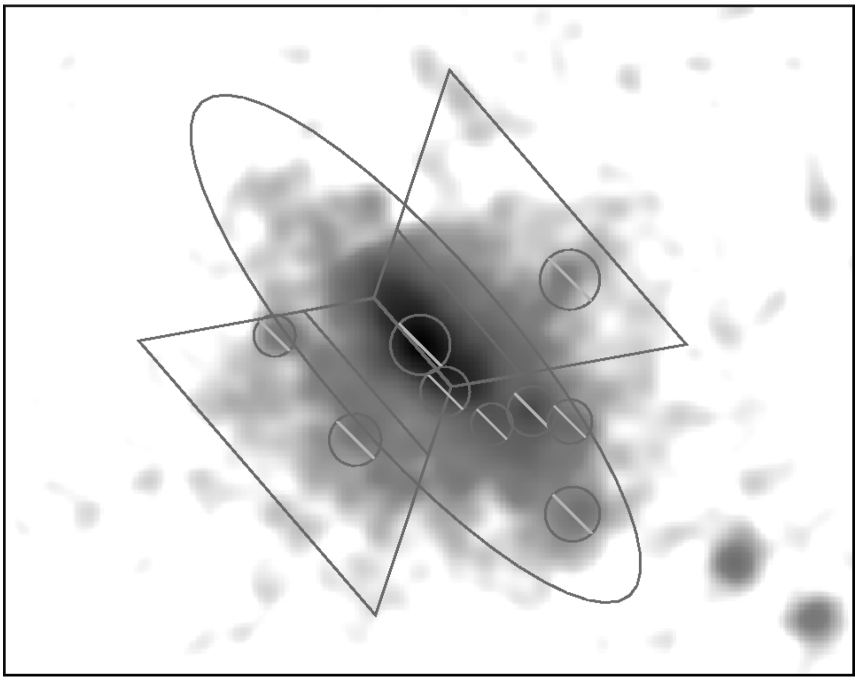

Figure 4: The extended soft X-ray halo of the nearby edge-on superwind galaxy NGC 4666, as observed by XMM-Newton EPIC in the 0.5-0.9 keV energy band. Point sources are shown by circles. The ellipse marks the optical (D_{25}) extension of the underlying galactic disk

on the energy input rate due to star formation in the underlying galactic disk. XMM-Newton X-ray observations are used by us to detect previously unknown extended halo emission due to hot gas and/or to re-visit galaxies with known (from earlier X-ray missions) extra-planar X-ray emission features but now with a hitherto unreached sensitivity. Reports on the status of our ongoing work were given by Dahlem et al. (2003) and Ehle (2005). A more detailed motivation and general introduction of our multi-wavelength project can be found in Dahlem et al. (2001) and Dahlem (2005). We detect interesting correlations of extra-planar X-ray emission with Hα spurs, polarization filaments and ordered magnetic field structures which support the idea of a common origin due to outflows. In two of our sample galaxies (NGC 4666, see Fig. 4, and NGC 3628) we find indications of a spatial offset between X-ray and Hα spurs. These might be explained in view of an outflow cone interacting with halo material and possibly showing temperature, density and excitation changes between the inner part and the outer walls of the cone. Our preliminary results on a comparison between energy densities of the thermal gas and that of the total magnetic field (see Ehle 2005), seem to indicate that in general the ratio between thermal and magnetic energy densities, the so-called plasma β parameter, is less than 1. This finding (which has been derived under a number of assumptions) is in contrast to the expectation formulated by Strickland & Stevens (2000) that large-scale magnetic fields do not appear to be dynamically important for the understanding of starburst driven galactic-scale outflows. More observations of magnetic fields in halos of actively star forming galaxies are certainly needed. On the other hand, estimates of the thermal energy density of the coronal gas still are based on CIE assumptions. We are therefore trying to fit the NIE self-consistent outflow model proposed by Breitschwerdt & Schmutzler (1999) to our XMM-Newton X-ray spectra extracted from the halo area of NGC 4666. As shown in Fig. 5, the model can already describe rather well the shape of the observed spectra and reveals two distinct humps at 0.6 and 0.9 keV caused by the O VII, O VIII and Fe L line complexes, respectively. The absolute flux, however, still requests further fine-tuning of the outflow model parameters. A similar spectral model (adjusted to XMM-Newton observations of NGC 3079) has been presented in Breitschwerdt (2003).

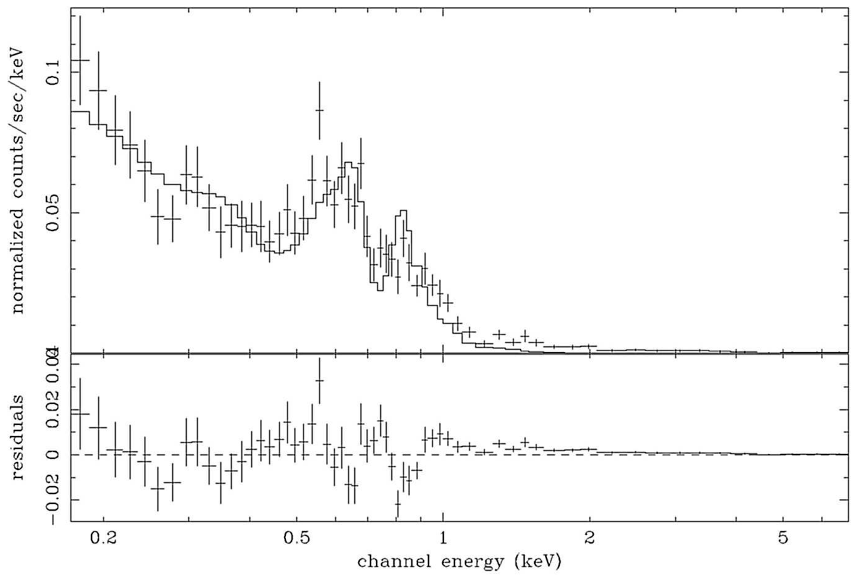

Figure 5: XMM-Newton EPIC-pn X-ray spectrum of the halo region of NGC 4666 (crosses = error bars) compared with a a self-consistent non-equilibrium emission galactic outflow model (solid line; provided by D. Breitschwerdt). The spectrum has been extracted from the outer parts of the cones on both sides of the disk, excluding point-like sources, as indicated in Fig. 4

4 Conclusions

There seems to be increasing evidence for the ubiquitous existence of diffuse X-ray emitting halos around the disks of starburst and normal spiral galaxies (if the amount of energy input in the underlying disk is high enough): supernova feedback in the disks creates, via blow-out and venting of hot gas from the disk, tenuous exponential atmospheres of density scale height $\sim 4-8$ kpc (cf. Strickland et al. 2004a). The soft X-ray halo emission is believed to be either this preexisting halo medium, or wind material compressed near the walls of the outflow. With the new generation of X-ray satellites, it has become possible to detect low surface brightness extended emission from coronal gas not only in galactic disks but also in tenuous galactic halos of actively star forming galaxies. The role of the magnetic field structure for the dynamics of the hot X-ray emitting gas is still a matter of debate but there are observational results showing a correlation of vertical magnetic field lines and extra-planar coronal gas. A further development of simulations taking into account all ingredients of the ISM and their interactions is needed to derive the 'real' physical parameters of the coronal gas.

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