The Origin and Properties of X-ray-emitting Gas in the Halos of both Starburst and Normal Spiral Galaxies

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Abstract. I discuss the empirical properties of diffuse X-ray emitting gas in the halos of both nearby starburst galaxies and normal spiral galaxies, based on high resolution X-ray spectral imaging with the Chandra X-ray Observatory. Diffuse thermal X-ray emission can provide us with unique observational probes of outflow and accretion processes occurring in star-forming galaxies, and their interaction with the inter-galactic medium. I consider both the spatial distribution of the diffuse X-ray emission in and around edge-on starburst galaxies with superwinds (e.g. surface brightness profiles, distribution with respect to Hα and radio emission), and its spectral properties (e.g. thermal or non-thermal nature, abundance ratios, temperatures and soft and hard X-ray luminosities). These results are discussed in the context of current theoretical models of supernova-driven superwinds, and compared to the more limited data on extra-planar hot gas around edge-on normal galaxies.

1. Introduction

Galaxy formation and evolution, in particular that of star-forming galaxies, can not understood in terms of isolated galaxies evolving independently of their environment. Even in the field galaxy population mass accretion, mass outflow and galaxy/galaxy interactions and mergers play a fundamental role. Merging of stellar systems is important, but it not the only significant process, and accretion from the inter-galactic medium (IGM) and gas and metal loss to the IGM can and probably does occur via purely gaseous processes even outside dense galaxy group and clusters (see e.g. Toft et al. 2002, Tremonti et al. 2004). To observe and quantify these processes in action we must observe the disk/halo interfaces, and halos (the galaxy/IGM interface) of local star-forming galaxies.

The diffuse thermal X-ray emission from gas with temperatures between $10^6$ and $10^8$ K is a particularly important probe of the conditions within the halos of star-forming galaxies.

- In the Chevalier & Clegg (1985) model for galactic superwinds driven by multiple core-collapse supernovae (SN) and massive star stellar winds, the merged, metal-enriched, SN and wind ejecta has a temperature within the starburst region of $T \sim 10^6 \epsilon/\beta K$, and thus would be a source of faint hard thermal X-ray emission ($E > 2$ keV). The fraction of SN mechanical energy thermalized is $\epsilon$ ($\lesssim 1$), while $\beta$ ($\gtrsim 1$) is the ratio of total mass added to the hot gas compared to that from SN and stellar wind ejecta.
The warm neutral and ionized gas in superwinds is observed to have velocities typically in the range $200 – 1000 \text{ km s}^{-1}$ (Heckman et al. 1990, 2000). This material is believed to be embedded within or at the boundary of a hot, metal-enriched, wind fluid that has even higher velocities (e.g. Strickland & Stevens 2000). Various processes will thus create soft thermal X-ray emission ($E < 2 \text{ keV}$), such as strong shocks ($T \sim 3.5 \times 10^6 \left[ v_{\text{shock}} / 500 \text{km s}^{-1} \right]^2$) or thermal conduction at interfaces between the warm gas and the hot wind fluid.

The depth of Milky-Way-like galaxy gravitational potential wells corresponds to a Virial temperature of $T_{\text{vir}} \sim 2 \times 10^6 \left( v_{\text{circ}} / 230 \text{km s}^{-1} \right)^2 \text{K}$. If gas inflowing from the IGM passes through an accretion shock, it will be heated to soft X-ray emitting temperatures.

In non-active galaxies this emission is purely collisionally excited, and thus diffuse X-ray emission on galactic scales is only created by mechanical energy return from SNe or stellar winds, or accretion into deep gravitational potential wells. The complicated processes of photo-ionization and radiative feedback from massive stars, so important at IR, optical and UV wavelengths, are negligible at X-ray wavelengths.

The diffuse thermal X-ray emission from star-forming galaxies is a mixture of continuum (bremsstrahlung and recombination) and line emission processes. For soft thermal plasmas ($6 \leq \log T(K) \leq 7$) line emission dominates the net emission for abundances $Z \gtrsim 0.2 Z_\odot$. As newly synthesized metals are believed to initially enter the hot phases of the ISM, X-ray observations will be vital in capturing galactic chemical evolution and IGM enrichment at work. Unfortunately the CCD-spectrometers on Chandra and XMM-Newton have too low a spectral resolution to resolve the strong line emission complexes from O, Fe, Ne, Mg and Si from the continuum over the energy range $0.5 – 2.0 \text{ keV}$, which complicates absolute element abundance measurements for such soft metal-bearing plasmas. Nevertheless, some useful spectral elemental diagnostics are possible with existing instrumentation, as I shall discuss.

Much of this contribution is based on our recent Chandra-based survey of 7 edge-on starbursts and 3 edge-on normal spirals (Strickland et al. 2004a,b), along with a preview of more recent work on diffuse hard X-ray emission from M82. Our findings on the starburst systems and their superwinds are presented in §3 and 4. Their properties are compared empirically to the diffuse X-ray properties of the normal spirals in §5. Conclusions drawn from this work, and some further questions raised by it, are summarized in §6.

2. Normal vs. Starburst

To understand the X-ray properties of normal star forming galaxies we must use a robust and physically-motivated method for separating more powerful objects (starbursts) from normal galaxies with very similar total star formation rates.

We define star-forming galaxies as starbursts using the widely-used IRAS $60 \mu\text{m}$ to $100 \mu\text{m}$ flux ratio $f_{60}/f_{100} \geq 0.4$ (e.g. Lehnert & Heckman 1995). There is a continuous distribution in the intensity in disk and irregular galaxies, but galaxies above this $f_{60}/f_{100}$ threshold have mean star formation intensities
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considerably greater than in a normal galaxy such as the Milky Way. This ratio is a measure of the luminosity-weighted mean dust temperature in these galaxies, but is well correlated to the inverse of the gas consumption timescale $\tau_{SF}$ due to star-formation, where a traditional and physically motivated definition of a starburst is $\tau_{SF} \leq \text{a few times } 10^8 \text{ yr.}$

The dust temperature is a function of the energy density in the interstellar radiation field, in particular the energy density in the UV which is dominated by massive stars in the presence of moderate to high levels star formation (see e.g. Désert et al. 1990). Thus the $f_{60}/f_{100}$ ratio is also a measure of the intensity of SF (i.e. rate per unit area or volume), rather than just the gross rate. It is thus complementary to other traditional methods of estimating the mean galactic SF rate per unit area based on total IR, H$_\alpha$ or non-thermal radio luminosities divided by some effective area (Dettmar 1993; Rand 1996; Dahlem et al. 2001; Rossa & Dettmar 2003).

That galaxies found by this method are not just classic nuclear starbursts like the archetypes M82 and NGC 253. For example, NGC 4631 ($f_{60}/f_{100} = 0.40$, see Rice et al. 1988; or $f_{60}/f_{100} = 0.53$ from Sanders et al. 2003) has only a weak nuclear starburst (Golla & Wielebinski 1994), but elevated levels of star formation occur across a large fraction of the optical-disturbed disk.

The starburst galaxies in our sample are M82, NGC 253, NGC 1482, NGC 3079, NGC 3628, NGC 4631 and NGC 4945. Other well-studied edge-on galaxies fulfilling this starburst definition are NGC 2146, NGC 3556 and NGC 5775. The three normal galaxies in our sample are NGC 891 and the lower mass spirals NGC 4244 and NGC 6503.

Although there are too few normal galaxies in this sample to robustly determine the diffuse X-ray properties of this class on its own, we can determine whether the spectral and spatial properties of any diffuse emission in these galaxies is similar to or different from the larger sample of starburst galaxies with known outflows. If the hot gas in the halos of normal galaxies is primarily generated by a mechanism other that SF-related disk outflow then their soft X-ray properties should be distinct from superwinds.

3. Hard diffuse X-ray emission in starbursts

Chandra observations of star forming galaxies have finally proven that the summed emission from populations of accreting compact objects (normal X-ray binaries, ultra-luminous X-ray sources, and in some cases low-luminosity AGN) dominate the hard X-ray emission ($E > 2 \text{ keV}$), see e.g. Swartz et al. (2003); Colbert et al. (2004). The luminosity function of these X-ray sources is such that the brightest point sources account for the majority of the net emission, so that Chandra observations of nearby galaxies typically resolve out $\sim 90\%$ of the total hard X-ray emission. The remainder is consistent with unresolved point source emission based on extrapolation from the observed luminosity function.

Nevertheless, Chandra observations have shown that in a few starburst galaxies there is genuine diffuse hard X-ray emission within the starburst region, in addition to the dominant point source emission, and in excess of any unresolved point source contribution. These galaxies are M82 (Griffiths et al. 2000, see also Fig. 1), NGC 253 (Weaver et al. 2002), and NGC 2146 (H. Mat-
sumoto, unpublished), all intense starbursts with SF rates per unit area near the upper limit observed for any starburst (Meurer et al. 1997). Studies of diffuse X-ray emission from galaxies have always concentrated on soft X-ray emission, so these hard X-ray detections may open a new window on an understudied but important phase of the ISM. We intend to perform a more systematic search for fainter diffuse hard X-ray emission in Chandra observations of less intense starbursts, but at present these three galaxies are the best examples of genuine diffuse hard X-ray emission.

The likely causes for appreciable diffuse hard X-ray emission in a star-forming galaxy can be divided between the action of low luminosity AGN (X-ray fluorescence and scattered AGN light) and processes associated with SNe (thermal emission from merged SN ejecta, non-thermal emission from inverse Compton [IC] scattering of IR photons off cosmic rays). In NGC 253 photoionization by the LLAGN is the most probable cause (Weaver et al. 2002). M82 has no LLAGN, and the close spatial association of the diffuse hard X-ray emission with the starburst region implicates SN activity (see Fig. 1 in Strickland 2004).

Is the hard emission in M82 consistent with theoretical models of hot gas in starburst galaxies? The initial Chandra ACIS-I study of this emission by Griffiths et al. (2000) emphasized a thermal interpretation of the hard continuum and a possible E=6.7 keV line emission from Fe XXV. As only gas with log T $\gtrsim$ 7.5 would produce appreciable 6.7 keV Fe emission, this implies $\epsilon/\beta \gtrsim 0.3$, i.e. efficient SN thermalization. However, the observed hard X-ray luminosity ($L_{2-10keV} \sim 5 \times 10^{39}$ erg s$^{-1}$) is at least an order of magnitude greater than expected for purely thermal emission from the starburst region (Strickland et. al, in preparation). Our analysis of new ACIS-S data and recalibrated ACIS-I data finds that the continuum is better fit by a non-thermal power law model, as expected from IC emission. Line emission from Fe is weak, but present in both datasets, although spread over the energy range 6.3 – 6.8 keV, suggesting emission from both neutral and highly ionized Fe. The hard X-ray spectrum...
is reminiscent of that of the Galactic Ridge (e.g. Park et al. 2004). Unlike the Galactic Ridge, whose energy source is a matter of debate, the flux in the ionized component of the Fe emission is consistent with predictions based on the Chevalier & Clegg (1985) model and M82’s inferred SN rate. Although the nature of the diffuse hard X-ray emission in the center of M82 is more complicated than initially thought, highly ionized \( \log T > 7.5 \) metal-bearing gas exists at the luminosity expected from superwind models, in the presence of a brighter but non-expected non-thermal diffuse continuum source. With the line-based spectral diagnostics possible with the Astro-E2 calorimeter \( (E/\Delta E \sim 1000 \text{ at } 6 \text{ keV}) \) it should be possible to measure the temperature of the 6.7 keV-emitting material independently of the non-thermal continuum, and hence directly constrain the efficiency of supernova feedback in a starburst.

4. Extra-planar soft diffuse X-ray emission from superwinds

There is a long history of soft X-ray studies of starburst galaxies with superwinds, leading up to modern 1″ spatial resolution studies with Chandra.

The diffuse soft X-ray luminosity is very well correlated with the star-formation rate \( \log L_{X,\text{TOT}}/L_{\text{FIR}} \approx -3.6 \pm 0.2 \) and \( \log L_{X,\text{HALO}}/L_{\text{FIR}} \approx -4.4 \pm 0.2 \) [e.g. Fig. 2], where the halo is defined as the region \(|z| > 2 \text{ kpc from the mid-plane}\), in good agreement with theoretical expectations (Strickland 2004).

Typically the soft diffuse X-ray emission is most extended along the minor axis of the host galaxy, and is spatially correlated with H\( \alpha \) emission. The maximum height to which emission is detected depends on the size of the host galaxy (Strickland et al. 2004b, Grimes et. al, in preparation). In dwarf starbursts \( z_{\text{max}} \sim 2 \text{ kpc} \) (e.g. Martin et al. 2002; Ott 2002). In more typical local starbursts \( \log L_{\text{FIR}}/L_\odot \sim 10.5 \) \( z_{\text{max}} \sim 10 – 20 \text{ kpc}, \) while \( z_{\text{max}} \sim 10 – 50 \text{ kpc} \) in ULIRGs. In the edge-on \( \log L_{\text{FIR}} \sim 10.5 \) starbursts the minor-axis X-ray surface brightness profiles are best fit by exponential models with scale heights \( H_{\text{eff}} \sim 2 – 4 \text{ kpc} \) \( (\text{density scale height } 4 – 8 \text{ kpc}). \) The data is inconsistent with the \( \Sigma \propto z^{-3} \) power law expected of a simple radial or conical volume-filling flow.

The emission is thermal, with clear metal line emission features, and typically has a characteristic temperature in the range 2 – 8 million degrees. Care needs to be taken when fitting to spectra containing spectrally distinct regions (Weaver et al. 2000). Even apparently spectrally uniform regions are not well described as single temperature plasmas in ionization equilibrium (Strickland et al. 2004a). Conservative analyses of the spectra do not allow absolute element abundances to be determined, but relative abundances, such as O or other \( \alpha \)-elements with respect to Fe, are well constrained (Martin et al. 2002; Strickland et al. 2004a). The super-Solar \( \alpha/\text{Fe} \) ratios observed are consistent with both massive star enrichment, or residual Fe depletion on dust (dust destruction time scales in the hot gas are comparable to wind flow times).

The spectral properties of the diffuse emission do vary spatially along the wind. Primarily this is due to variations in intervening absorption column (by a factor \( \gtrsim 10 \) in these edge-on galaxies, when moving from emission within the absorbed disk plane to extra-planar emission. There appears to be a weaker (factor \( \sim 2 \)) drop in effective temperature from disk to halo. Spectral variation within the halo is generally negligible, although weak variations with \( z \) are see
in a few cases (Strickland et al. 2004a). The combination of spectral and surface brightness variations are not consistent with the adiabatic expansion of a volume-filling X-ray emitter (e.g. Strickland et al. 1997).

In all cases with good signal to noise data, the Chandra observations reveal genuine spatial structure in the superwind soft X-ray emission (Fig. 1), on scales similar to the structure in optical nebular emission (Strickland et al. 2000, 2002; Cecil et al. 2002; Schurch et al. 2002; Strickland et al. 2004a). The best interpretation of this data is in terms of the soft X-ray emission arising in low volume regions in the vicinity of obstacles in the flow: the walls, and any dense clouds within the wind. The large spurs and filaments are mainly the limb-brightened walls of the outflow.

The combination of spatial structure, close relationship to optical nebular emission, exponential surface brightness profiles, weak spectral variation and high apparent gas phase $\alpha$/Fe abundance ratios force the following conclusions regarding the soft X-ray emitting material in superwinds: It is not a volume-filling wind of the kind modeled by Suchkov et al. (1996). The majority of the emission must come from relatively low volume filling factor, $0.01 < \eta < 0.3$ (more work needs to be done to better quantify these values). It may only contain a small fraction of the energy and metal content of the wind. The soft X-ray arise in some form of interaction between dense ambient gas in clouds or at the outflow walls and the volume-filling tenuous merged SN ejecta fluid that really drive the superwind. Much of our current work is exploring methods for distinguishing between the multiple plausible wind/ambient ISM interaction models (shock-heated ambient gas, conductively evaporated and heated ambient gas, or shock-compressed ejecta fluid) implied by the Chandra data.

### 5. Diffuse X-ray emission in both normal and starburst galaxies

We detect extra-planar (|z| > 2 kpc) hot gas in only one of the three normal galaxies in Strickland et al. (2004a): NGC 891, which has a similar $L_{X,\text{HALO}}/L_{\text{FIR}}$ ratio to the starbursts (Fig. 2a). This is interesting, as one might expect more halo X-ray emission from galaxies with more intense star formation. However, both NGC 4244 and NGC 6053 have lower star formation rates than NGC 891, and they could plausibly have hot halos at luminosities consistent with this relationship that would not have been detected in these observations.

The minor axis extent of the diffuse X-ray emission (measured by scale height or with an isophotal size) scales with the size of the host galaxy (e.g. optical $D_{25}$ or K-band half light radius). Both NGC 891 and NGC 6503 are consistent with the starburst trends. The size of the star forming region within the disk has no influence on the minor axis extent of the X-ray-emitting gas.

We find reasonably good correlations between the mean and halo-region X-ray surface brightness and mean SF rate/area in the disk (based on $f_{60}/f_{100}$, $L_{\text{FIR}}/D_{25}^2$ or non-thermal radio flux and size $f_{\text{radio}}/D_{\text{radio}}^2$). This is similar to the qualitative correlation between the prevalence of extra-planar Hα emission or dust with mean SF rate per unit area (Dettmar 1993; Rand 1996; Howk & Savage 1999). It is tempting to interpret our X-ray results in terms of a critical SF (or SN) rate per unit area required for superbubble blow out from a disk galaxy. However, this correlation is possibly a combination of the
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Figure 2. (a) Disk and halo diffuse X-ray luminosity per unit galaxy mass, as a function of FIR luminosity, effectively the total SF rate (disk $|z| < 2$ kpc: open circles, halo: filled circles). (b) Halo-region diffuse X-ray flux to host galaxy FIR flux ratio, as a function of the mean SF rate per unit area in the host galaxy. (c) Minor axis surface brightness scale height $H_{\text{eff}}$ as a function of the host galaxy optical diameter $D_{25}$. In both plots a and c the dashed line is not a fit, and is shown purely to show what unit slope is.

6. Conclusions and remaining questions

Chandra observations of starburst galaxies have answered some of the pressing questions regarding X-ray emitting gas in superwinds. The very hot plasma predicted by the Chevalier & Clegg (1985) model has probably been detected in M82 at expected flux levels in the 6.7 keV Fe line, along with non-thermal continuum emission. Soft X-ray emission in winds is of low volume filling factor, as is associated with some form of wind fluid interaction with cooler denser ambient disk and halo gas. Strongly mass-loaded wind models can be ruled out.

The extra-planar X-ray luminosity of the approximately edge-on star-forming disk galaxies in our sample is directly proportional to the host galaxy’s SF rate. The vertical extent of the diffuse X-ray emission is proportional to the host galaxy’s size. We definitely need more X-ray observations of edge-on normal star-forming disk galaxies, especially if we are to constrain accretion models. What we can say with the existing observations is that the properties of the diffuse soft X-ray-emitting plasma in normal galaxies appears very similar to that in starbursts, scaled proportionally to lower SF rates. The existing non-detections of extra-planar hot gas do not prove that there is no hot halo gas.

With the aim of being provocative, I will close by asking some questions inspired by these results. How similar can the physical conditions in a normal galactic fountain be to a superwind? Can warm and hot gas filling factors be low in the halo of NGC 891, despite the apparent smoothness of the emission? Are the majority of non-detections of extra-planar warm ionized gas, hot ionized gas, radio emission, and dust significant? In other words, is there no extra-planar plasma, or is it just too faint to detect?
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