DIFFUSE X-RAY EMISSION FROM STAR-FORMING GALAXIES

KARTIČK C. SARKAR\textsuperscript{1,2}, BIMAN B. NATH\textsuperscript{1}, PRATEEK SHARMA\textsuperscript{2}, and YURI SHCHEKINOV\textsuperscript{3}

\textsuperscript{1}Raman Research Institute, Sadashiva Nagar, Bangalore 560080, India; kcsarkar@rri.res.in
\textsuperscript{2}Joint Astronomy Programme and Department of Physics, Indian Institute of Science, Bangalore, 560012, India
\textsuperscript{3}P. N. Lebedev Physical Institute, 53 Leninskiy Prospekt, 119991, Moscow, Russia

Received 2015 December 17; accepted 2016 January 24; published 2016 February 11

ABSTRACT

We study the diffuse X-ray luminosity ($L_X$) of star-forming galaxies using two-dimensional axisymmetric hydrodynamical simulations and analytical considerations of supernovae-(SNe)-driven galactic outflows. We find that the mass loading of the outflows, a crucial parameter for determining the X-ray luminosity, is constrained by the availability of gas in the central star-forming region, and a competition between cooling and expansion. We show that the allowed range of the mass loading factor can explain the observed scaling of $L_X$ with star formation rate (SFR) as $L_X \propto \text{SFR}^2$ for SFR $\gtrsim 1 \, M_\odot \, \text{yr}^{-1}$, and a flatter relation at low SFRs. We also show that the emission from the hot circumgalactic medium (CGM) in the halo of massive galaxies can explain the large scatter in the $L_X$–SFR relation for low SFRs ($\lesssim$few $M_\odot \, \text{yr}^{-1}$). Our results suggest that galaxies with small SFRs and large diffuse X-ray luminosities are excellent candidates for the detection of the elusive CGM.

Key words: galaxies: general – galaxies: halos – galaxies: star-forming – ISM: jets and outflows – X-rays: galaxies

1. INTRODUCTION

Understanding the feedback mechanisms in galaxies is crucial in order to explain the evolution of galaxies (Larson 1974; Dekel & Silk 1986; Sharma & Nath 2013) and the enrichment of the intergalactic medium (IGM; Tegmark & Silk 1993; Nath & Trentham 1997). It has been observed (Strickland et al. 2002; Strickland & Heckman 2007) and noticed in numerical simulations (Hopkins et al. 2012; Sarkar et al. 2015, hereafter S15) that a significant fraction ($\sim$0.3–0.5) of the input mechanical energy is stored in a hot ($T \gtrsim 10^6$ K), X-ray emitting gas. Therefore, it is necessary to decipher the origin of diffuse X-ray emission from star-forming galaxies to understand the feedback mechanisms.

In the case of stellar feedback processes producing a gaseous outflow, the hot gas can form in (1) the central region where star formation occurs, (2) the free wind, (3) the interaction zone between the wind and halo gas surrounding the galaxy, and (4) the interaction region of wind and dense clouds (Suchkov et al. 1994, 1996; Strickland & Stevens 2000; Cooper et al. 2008, 2009; Thompson et al. 2016). In addition, there is a non-negligible contribution from the hot halo gas surrounding the galaxies. For well-resolved galaxies, this basic scenario can be used to investigate the kinematic properties of the wind. For example, using X-ray observations, Strickland & Heckman (2007) found that the velocity of the outflow in the central region ($\sim$100 pc) of M82 can be as large as $\sim$10$^3$ km s$^{-1}$ and the mass outflow rate in the hot phase can be $\sim$1/3 of the star formation rate (SFR) in that galaxy.

However, some aspects of the diffuse X-ray emission remain puzzling. Using 2D axisymmetric simulations for a galaxy with SFR $\sim 1 \, M_\odot \, \text{yr}^{-1}$, Suchkov et al. (1994) found that the shocked halo emission dominates over the emission from the central part. In contrast, using a full 3D simulation of M82 (SFR $\sim 10 \, M_\odot \, \text{yr}^{-1}$) Cooper et al. (2008) showed that most of the emission comes from the central region and free wind rather than the halo. Cooper et al. (2008, 2009) also noticed that a part of the emission comes from the interaction of clouds and the high velocity wind. However, a quantitative description of this emission is unavailable.

Another problem involves the scaling relation between the diffuse X-ray luminosity (not associated with point sources directly or indirectly) and the SFR. A thermally driven wind model (Chevalier & Clegg 1985, hereafter CC85)\textsuperscript{4} suggests that the hot gas density at the central region of galactic wind is $\propto$ SFR, and therefore, the X-ray luminosity $\propto$ SFR$^2$. The temperature of the gas related to the wind or shocked halo is $\lesssim$2 $\times$ 10$^7$ K which emits mostly in the soft band (0.5–2.0 keV). A recent observational study of diffuse X-ray emission, however, suggests that the soft-X-ray luminosity, $L_X$, $\propto$ SFR (Mineo et al. 2012, hereafter M12), though other scalings cannot be ruled out. Zhang et al. (2014) and Busardi et al. (2015) attempted to reconcile the observations with the expected scaling by adjusting parameters such as the mass loading factor (MLF; mass outflow rate/SFR = $\beta$) and the thermalization efficiency ($\alpha$). They suggested an inverse dependence of $\beta$ on SFR in order to explain the observed $L_X$–SFR relation. However, the physical origin for such an inverse relation remains unexplained.

Yet another problem is that galaxies with low SFR ($\lesssim$few $M_\odot \, \text{yr}^{-1}$) show a flatter $L_X$–SFR relation with large scatter in the diffuse X-ray luminosity (Wang et al. 2015, hereafter W15), implying that other factors beyond stellar feedback contribute significantly to X-ray emission.

In this Letter, we constrain the MLF based on the amount of interstellar medium (ISM) mass available and by the requirement that the cooling time be longer than the outflow expansion time. Using this, we show that at large SFRs the X-ray luminosity ($L_X$) indeed scales as SFR$^2$, but at smaller SFRs the X-ray emission from the circumgalactic medium (CGM; which is insensitive to SFR) starts to dominate. This behavior can lead to the observed $L_X \propto$ SFR or even flatter relation if one fits a single power law to observations.

\textsuperscript{4} Note that the CC85 model with a smooth thermalized wind is only applicable for SFRs larger than a critical value ($\approx$0.1 $M_\odot \, \text{yr}^{-1}$) (Sharma et al. 2014). Therefore, CC85 is a good approximation in the range of SFRs of our interest.
2. MASS LOADING OF OUTFLOWS

Consider galaxies with outflows driven by thermal feedback from star formation, which we model as a thermal wind within a central region of size $R$ (following CC85). The energy and mass injection in the central zone is parametrized by $M$ and $E$, which are, respectively, the mass deposition rate and the energy deposition rate, and are given by $M = \beta SFR$ and $E = 5 \times 10^{52} \alpha SFR$ (assuming a Kroupa/Chabrier mass function, and an efficiency $\alpha \approx 0.3$ for energy deposition; here $E$, $M$ and SFR are in COS units).

The X-ray luminosity of a galactic wind sensitively depends on the MLF ($\beta$) (Zhang et al. 2014), which is governed by the following considerations. (1) Stellar evolution models suggest that stellar winds and supernova ejecta (without entrainment from the surrounding ISM) contribute to $\beta_0 \approx 0.3$ (Leitherer et al. 1999) and (2) the outflowing gas entrains mass from the surrounding ISM. However, the entrained mass (due to conduction and KH instabilities) cannot be larger than the total ISM mass $M_{\text{g}}(=4\pi \mu m_p n_{\text{ism}} R^3/3)$ available within the central starburst region of radius $R$. Therefore, an upper limit of MLF is given by

$$\beta_{\text{global}} = \beta_0 + \frac{M_{\text{g}}/\Delta t}{SFR} = 0.3 + 0.06 \times \frac{n_{\text{ism}} R_{100pc}^3}{SFR_{M_{\odot}yr^{-1}} \Delta t \text{Myr}},$$

where $n_{\text{ism}}$ is the ambient ISM number density and $\Delta t$ is the age of the starburst. (3) A further constraint arises from the cooling time of this central gas, which must be longer than the expansion time, otherwise most mass will condense radiatively and drop out of the outflow (see Equation (10) of Thompson et al. 2016; for the curve shown in Figure 1, we use a wind opening angle of 60°). (4) A related constraint is that the total X-ray luminosity of the central region ($\approx 4\pi n_e^2 \Lambda(T_c) R^3/3$; where $n_e = 0.3 M_{\odot}^{1/2} E^{-1/2} R^{-2}/\mu m_p$ is the central ISM number density, $\mu = 0.6$ is the mean molecular weight, $\Lambda$ is the X-ray emission function (erg s$^{-1}$ cm$^{-3}$), and $T_c = 1.4 \times 10^4 \alpha/\beta$ is the central temperature; see CC85) should be smaller than the energy deposition rate ($\dot{E}$). This gives an upper limit on MLF, namely,

$$\beta_{\text{max, X-ray}} = \left( \frac{13.5 \alpha_{0.1} R_{100pc}}{SFR_{M_{\odot}yr^{-1}} \Lambda_{-23}(T, Z)} \right)^1,$$

where $\Lambda_{-23}(T, Z)$ is the emission function at a particular X-ray energy band (in units of $10^{-23}$ erg s$^{-1}$ cm$^{-3}$), temperature ($T$) and metallicity ($Z$). For the calculation of $\beta_{\text{max, X-ray}}$ in Figure 1, we fix $\Lambda_{-23}(T_c, Z_c) = 1$. Note that argument (4) is not completely independent of argument (3).

In the case of high $\beta$, the outflowing gas has a large ram pressure ($\propto M^{1/2} E^{1/2} \propto \beta^{1/2}$) on the surrounding gas, and is likely to entrain more gas. It is therefore reasonable to assume that $\beta$ is likely to attain the maximum allowed value under the above considerations (arguments 2, 3, and 4 in the previous paragraph). Figure 1 shows various threshold values of $\beta$ as a function of SFR. Open circles show the maximum values of $\beta$ allowed by these considerations.

3. SIMULATION DETAILS

We perform 2D axisymmetric hydrodynamic simulations using PLUTO (Mignone et al. 2007). We simulate only one quadrant of an MW-type galaxy (total mass $M_{\text{gal}} = 10^{12} M_{\odot}$). The initial condition for the galaxy is in dynamical equilibrium with a warm, rotating disk ($T \sim 4 \times 10^4$ K; with Solar metallicity) and a hot gaseous halo ($T = 3 \times 10^6$ K; with 0.1 Solar metallicity) surrounding the galaxy. We vary SFR for the same disk/halo properties. The disk gas is not allowed to cool if it is not shocked/perturbed; i.e., unless $\sqrt{\vec{v}_e^2 + \vec{\Omega}^2} \geq 20$ km s$^{-1}$. Other details of the model can be found in S15.

The supernovae (SNe) energy is deposited continuously in the form of thermal energy in a spherical region of radius $R$ at the center of the galaxy. In reality, most of the SNe occurs in a low-density medium created by the previous SNe explosions and stellar winds. To mimic this, we create an artificially low-density medium ($10^{-3} n_{\text{halo}}$ cm$^{-3}$) at $t = 0$ for $r \leq R$ (in local pressure equilibrium with the region outside) and then deposit the SNe energy and mass (with $Z_c$) inside it. This also prevents artificial cooling losses due to lack of sufficient numerical resolution. For estimating the X-ray emission function ($\Lambda(T, Z)$), we use the MEKAL model at 0.2 and 1.0 $Z_c$, and linearly interpolate for all other metallicities (from 0.1 to 1.0 $Z_c$).

4. RESULTS

Figure 2 shows snapshots of density, temperature, and soft X-ray emissivity for $SFR = 5 M_{\odot}$ yr$^{-1}$ and background halo density $\rho_{\text{halo}} = 3 \times 10^{-4} m_p$ cm$^{-3}$ at $t = 20$ Myr. It shows a typical structure containing free wind, termination shock, shocked wind, shocked halo, and unshocked halo as labelled in the left panel (Weaver et al. 1977). The soft-X-ray (0.5–2.0 keV) emissivity (rightmost panel) shows the origin of X-ray emission in a typical galactic wind. It shows that the soft-X-ray emissivity of the central region is very high and is followed by shocked wind, shocked halo, and halo region.

We find that the luminosity of the central region becomes constant after $t \geq 1$ Myr (which is essentially the time to set up a steady wind at the center for a constant mass and energy injection rate, and is given by the sound crossing time
The next important contribution toward X-ray emission comes from the CGM, which contains a significant fraction of the missing baryonic mass, as seen in X-ray (Anderson & Bregman 2011; Dai et al. 2012; Bogdán et al. 2013) and absorption studies (Bordoloi et al. 2014; Borthakur et al. 2015).

The CGM density profile can be approximated as $n_0 (1 + r/r_c)^{-3/4}$, where $n_0$ is the central density, $r_c$ the core radius, and $r$ the radius. This approximation is accurate only for $r < r_c$, where the density is not quite uniform. Results from our simulations are well fit by,

$$L_{X,C} / \text{erg s}^{-1} \approx 3 \times 10^{39} \alpha^{-1} \beta^3 \text{SFR}^2 R_{500pc} \Lambda_{-23}(T, Z). \quad (3)$$

The CGM density profile can be approximated as $n_0 (1 + r/r_c)^{-3/4}$, with a core radius $r_c$ ($\approx 3$ kpc) and central density $n_0$ (see Figure 1 of S15). While this is clearly an approximation, the density values are not that different from estimates in the literature (e.g., Sharma et al. 2012; Fang et al. 2013; Gatto et al. 2013). If the CGM gas is spread over a large length scale $r/r_c = x \gg 1$, then the X-ray luminosity can be expressed in terms of $M_{\text{CGM}} (\approx 10^{10} M_{\odot})$, the total CGM gas mass (we express the dependence of $L_{X,C}$ on the extent of the CGM in terms of $M_{\text{CGM}}$), as $L_{X,\text{CGM}} \approx 5.4 \times 10^{40} n_0^{-4/3} r_c^{-1} \Lambda_{-23} M_{\text{CGM}}^{2/3} \text{erg s}^{-1}$, where $n_0 = 10^{-3} \text{ cm}^{-3}$ and $r_c = 3 r_c$ kpc. However, our simulation results show that the actual luminosity from CGM is somewhat less than this, because of the approximation ($x \gg 1$) used in arriving at it, and is better represented by

$$L_{X,\text{CGM}} / \text{erg s}^{-1} \approx 8.6 \times 10^{39} n_0^{-4/3} r_c^{-1} \Lambda_{-23}(T, Z) M_{\text{CGM}}^{2/3}. \quad (4)$$

Next, we compare the X-ray luminosity from our simulations (scaled according to Equations (3) and (4) for different star formation and CGM properties) with the observed data. Figure 3 shows the $L_{X}$–SFR relation from our models. The green and blue lines show $L_{X,C}$ for the cases of $\beta = 0.3$ and the maximum $\beta$ (circles in Figure 1), respectively. We find that the data from M12, shown in red squares, are explained by $L_{X,C}$ for the range of $0.3 \leq \beta \leq \beta_{\text{max}}$, where $\beta_{\text{max}}$ is determined by the available ISM mass and the radiative cooling time, as discussed in Section 2, whereas, a higher $\beta$ for smaller SFRs due to the ISM mass loading makes the relation shallower at smaller SFRs. The data, which have hitherto been fit with a linear scaling between $L_X$ and SFR, actually belong to two different regimes: a quadratic scaling at large SFRs and a flattening at smaller SFRs. In fact, the constraint of MLF from available

Figure 2. Snapshots of density (left panel), temperature (middle panel), and soft-X-ray (0.5–2.0 keV) emissivity (right panel) contours at $r = 20$ Myr for SFR = 5 $M_{\odot}$ yr$^{-1}$ and central halo density $n_0 = 3 \times 10^{-3} \text{ cm}^{-3}$ with total grid points = 512$^3$. The labels in the left panel are as follows: FW—Free Wind, SW—Shocked Wind, and SH—Shocked Halo. Note that we have used a colorbar between $10^{-21} \text{ erg s}^{-1} \text{ cm}^{-3}$.
Figure 4. Data from W15 along with curves for total diffuse X-ray luminosities for different values of \( M_{\text{CGM}} \). These correspond to the same models as in Figure 3, but normalized to \( M_{\text{CGM}} = M_\ast \).

We also notice that the curves in Figure 4 show a negative slope for high-SFR galaxies (on the left), which is consistent with the observed trend for high-SFR galaxies in W15.

5. DISCUSSION

Our key result is that the diffuse X-ray emission from star-forming galaxies can be understood in terms of contributions from the central thermalized wind (extending over \( \sim 100 \) pc) and the extended CGM. For higher SFRs \( L_X \propto \text{SFR}^2 \), whereas, the CGM contribution dominates for \( \text{SFR} \lesssim (1 \, M_\odot \text{yr}^{-1}) \) and accounts for the flattening of the \( L_X \)-SFR relation at low SFRs. Our model also predicts that the relation can be even flatter with a large scatter, depending on the halo properties. Since the CGM mass is expected to increase with the stellar/halo mass, at smaller SFRs a higher \( L_X \) can result from the CGM contribution. In fact, the galaxies with low SFRs but high \( L_X \) are likely to contain a large amount of CGM gas at temperatures of a few million degrees K, and are good candidates for spiral galaxies with a detectable X-ray emitting CGM (few such systems are reported by Anderson & Bregman 2011; Bogdán et al. 2013).

The X-ray luminosity from the CGM (Equation (4)) depends on the CGM gas mass, density, and temperature. We find that for a typical range in temperature (as found in, say, W15) of \( 2 - 8 \times 10^6 \) K, the \( L_{X,\text{CGM}} \) varies between \( 3 \times 10^{38} - 2.4 \times 10^{40} \) erg s\(^{-1} \), for \( M_{\text{CGM}} = 10^{10} M_\odot \). This spread arises from (1) the difference in emissivity with temperature and (2) the density profile of CGM gas at different temperatures. Figure 3 shows that this spread in X-ray luminosity from the CGM gas can explain the data. However, we should keep in mind that the spread in the data (Figure 4) can partly arise from the spread in the relation between SFR and galaxy dynamical mass, which is likely related to \( M_\ast \) (Karachentsev & Kaisina 2013). We also note that the central SFR used in our models is an underestimate of a disk-wide SFR. This can also be responsible for the spread in the observed data.

It is generally believed that the CGM around low-mass galaxies \( (M_\ast \lesssim \text{few} \times 10^9 M_\odot) \) would have a low virial temperature (few \( 10^5 \) K), which would make the CGM vulnerable to radiative cooling because the cooling time would become less than the dynamical time of the galaxy (Singh et al. 2015). However, hot CGM around low-mass galaxies can be formed from the hot and low-density material ejected from disk SNe, which does not have sufficient energy to escape the galactic potential but has a long cooling time. This rejuvenated halo around low-mass galaxies may give rise to the X-rays seen in low-mass galaxies (which are also low-SFR galaxies, in the presented data). The spread in the \( L_X \)-SFR relation at the low-SFR end can be partly due to the ill-understood, complex thermodynamic state of such low speed outflows.

Though observations of the total X-ray emission (0.5–8.0 keV) (Mineo et al. 2014) show a linear relation, it is, however, supposed to be contaminated by high-mass X-ray binaries (HMXB; Grimm et al. 2003) and should best be considered as an indicator to the SFR (since, number of HMXBs \( \propto \text{SFR} \)) rather than the diffuse X-ray related to the galactic wind.

We also note that the linear relation of X-ray luminosity from the shocked wind and halo as observed in highly inclined galaxies by Strickland et al. (2004), Tüllmann et al. (2006), and Li & Wang (2013) have to be studied separately because the...
soft-X-ray emission from the central part of these galaxies is heavily absorbed by the galactic disk and does not represent the total emission. We will address these issues in detail in a future paper.

We are indebted to Daniel Q. Wang for sharing data with us and for his useful comments. We also thank Nazma Islam for useful discussions. This work is partly supported by the DST-India grant No. Sr/S2/HEP-048/2012 and an India-Israel joint research grant (6-10/2014[IC]). Y.S. acknowledges support from RFBR through 15-02-08293 and 15-52-45114, and partial support from the Grant of the President of RF for the Leading Scientific Schools NSh-4235.2014.2.

REFERENCES

Anderson, M. E., & Bregman, J. N. 2011, ApJ, 737, 22
Bogdán, Á, Forman, W. R., Vogelsberger, M., et al. 2013, ApJ, 772, 97
Bordoloi, R., Tumlinson, J., Werk, J. K., et al. 2014, ApJ, 796, 136
Borthakur, S., Heckman, T., Tumlinson, J., et al. 2015, ApJ, 813, 46
Bustard, C., Zweibel, E. G., & D’Onghia, E. 2015, ApJ, in press (arXiv:1509.07130)
Chevalier, R. A., & Clegg, A. W. 1985, Nat, 317, 44
Cooper, J. L., Bicknell, G. V., & Sutherland, R. S. 2008, ApJ, 674, 157
Cooper, J. L., Bicknell, G. V., Sutherland, R. S., & Bland-Hawthorn, J. 2009, ApJ, 703, 330
Dai, X., Anderson, M. E., Bregman, J. N., & Miller, J. M. 2012, ApJ, 755, 107
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Fang, T., Bullock, J., & Boylan-Kolchin, M. 2013, ApJ, 762, 20
Gatto, A., Fraternali, F., Read, J. I., et al. 2013, MNRAS, 433, 2749
Grimm, H-J., Gilfanov, M., & Sunyaev, R. 2003, MNRAS, 339, 793
Hopkins, P. F., Quataert, E., & Murray, N. 2012, MNRAS, 421, 3522
Karachentsev, I. D., & Kaisina, E. I. 2013, A& A, 146, 46
Larson, R. 1974, MNRAS, 169, 229
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJSS, 123, 3
Li, J., & Wang, Q. D. 2013, MNRAS, 428, 2085
Mignone, A., Bodo, G., Massaglia, S., et al. 2007, ApJS, 170, 228
Mineo, S., Gilfanov, M., Lehmer, B. D., Morrison, G. E., & Sunyaev, R. 2014, MNRAS, 437, 1698
Mineo, S., Gilfanov, M., & Sunyaev, R. 2012, MNRAS, 426, 1870
Nath, B. B., & Trentham, N. 1997, MNRAS, 291, 505
Sarkar, K. C., Nath, B. B., Sharma, P., & Shchekinov, Y. 2015, MNRAS, 448, 328
Sharma, M., & Nath, B. B. 2013, ApJ, 763, 17
Sharma, P., McCourt, M., Parrish, I. J., & Quataert, E. 2012, MNRAS, 427, 1219
Sharma, P., Roy, A., Nath, B. B., & Shchekinov, Y. 2014, MNRAS, 443, 3463
Singh, P., Nath, B. B., Majumdar, S., & Silk, J. 2015, MNRAS, 448, 2384
Strickland, D. K., & Heckman, T. M. 2007, ApJ, 658, 258
Strickland, D. K., Heckman, T. M., Colbert, J. M., Hoopes, C. G., & Weaver, K. A. 2004, ApJ, 606, 829
Strickland, D. K., Heckman, T. M., Weaver, K. A., Hoopes, C. G., & Dahlem, M. 2002, ApJ, 560, 689
Strickland, D. K., & Stevens, I. R. 2000, MNRAS, 314, 511
Suchkov, A. A., Balsara, D. S., Heckman, T. M., & Leitherer, C. 1994, ApJ, 430, 511
Suchkov, A. A., Berman, V. G., Heckman, T. M., & Balsara, D. S. 1996, ApJ, 463, 528
Tegmark, M., & Silk, J. 1993, ApJ, 417, 54
Thompson, T. A., Quataert, E., Zhang, D., & Weinberg, D. H. 2016, MNRAS, 455, 1830
Tüllmann, R., Breitschwerdt, D., Rossa, J., Pietsch, W., & Dettmar, R.-J. 2006, A&A, 457, 779
Wang, Q. D., Li, J., Jiang, X., & Fang, T. 2015, MNRAS, in press (arXiv:1512.02655)
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377
Werk, J. K., Prochaska, J. X., Tumlinson, J., et al. 2014, ApJ, 792, 8
Zhang, D., Thompson, T. A., Murray, N., & Quataert, E. 2014, ApJ, 784, 93