Mon. Not. R. Astron. Soc. **000**, 1–8 (2009) Printed 10 November 2010 (MN LaTeX style file v2.2)

The similarity of observed X-ray coronae associated with $L_\star$ disc and elliptical galaxies

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10 November 2010

ABSTRACT

The existence of hot, X-ray luminous gaseous coronae surrounding present day $L_\star$ galaxies is a generic prediction of galaxy formation theory in the cold dark matter cosmogony. While extended X-ray emission has been known to exist around elliptical galaxies for a long time, diffuse extra-planar emission has only recently been detected around disc galaxies. We compile samples of elliptical and disc galaxies that have *Chandra* and *XMM-Newton* measurements, and compare the scaling of the coronal X-ray luminosity ($L_{\rm X}$) with both the K-band luminosity ($L_{\rm K}$) and the coronal X-ray temperature ($T_{\rm X}$). The X-ray flux measurements are corrected for non-thermal point source contamination by spatial excision and spectral subtraction for resolved and unresolved sources respectively. We find that the properties of the extended X-ray emission from galaxies of different morphological types are similar: for both elliptical and disc galaxies, the $L_{\rm X}-L_{\rm K}$ and $L_{\rm X}-T_{\rm X}$ relations have similar slope, normalisation and scatter. The observed universality of coronal X-ray properties suggests that the bulk of this emission originates from gas that has been accreted, shock-heated and compressed during the assembly of the galaxy and that outflows triggered by stellar processes make only a minor contribution to the X-ray emission. This reservoir of cooling gas is a potential source of morphological transformation; it provides a fresh supply of material for discs to grow around galaxies of all morphological types.

Key words: galaxies:formation – galaxies: haloes – galaxies: cooling flows – galaxies: intergalactic medium

1 INTRODUCTION

In the cold dark matter (CDM) cosmogony, galaxy formation is a continuous process fuelled by the accretion of material in the form of dark matter, stars and gas. Building upon the general idea of hierarchical clustering proposed by White & Rees (1978), White & Frenk (1991, hereafter WF91) developed an analytical framework to calculate galaxy formation in a CDM universe under certain simplifying assumptions, such as spherical symmetry and isothermal density profiles. In this model, when sufficiently massive dark matter halos collapse, their associated gas is shock-heated to the virial temperature of the halo, forming a hot, quasi-hydrostatic corona from which gas slowly cools through line emission and thermal bremsstrahlung, feeding a disc around the growing central galaxy. A central prediction of this model is that the cooling radiation from present-day $L_\star$ galaxies should escape as soft ($k_{\rm B}T_{\rm X} \sim 0.1\,{\rm keV}$) X-rays, and thus that these galaxies should be surrounded by extended X-ray coronae.

Although in the WF91 model there is no distinction between the nature of the coronae surrounding disc or elliptical galaxies, isolated massive spiral galaxies were identified by Benson et al. (2000) as particularly promising targets for detecting X-ray coronae. However, the *Einstein* and *ROSAT* observatories failed to provide any evidence for this, setting instead upper limits (e.g. Bregman & Glassgold 1982; Vogler et al. 1995; Bregman & Houck 1997; Fabbiano & Juda 1997; Benson et al. 2000). The first detections of circumgalactic X-ray emission around local disc galaxies were finally possible with the *Chandra* and *XMM-Newton* telescopes but this emission turned out to be one to two orders of magnitude fainter than predicted by WF91 (Strickland et al. 2004; Wang 2005; Tüllmann et al. 2006; Li et al. 2007; Jeltema et al. 2008; Owen & Warwick 2009; Rasmussen et al. 2009; Sun et al. 2009).

It is widely believed that the most likely source of soft X-ray

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emission in many of these disc galaxies is outflowing gas driven by energy from Type II supernovae (SNe), rather than a cooling inflow from a hot corona. The evidence for this is the observed correlation between star formation rate and coronal soft X-ray luminosity. In some particularly spectacular cases, such as M82, the X-ray emission exhibits a biconical morphology suggestive of outflows (Strickland et al. 2004), and this could also be the case for our own Milky Way (Bland-Hawthorn & Cohen 2003; Su et al. 2010).

Since the existence of hot gaseous coronae around sufficiently massive galaxies is a quintessential component of the WF91 model (and thus of the many semi-analytic models based on it), failure to detect the predicted X-ray emission poses an interesting problem for the canonical view of galaxy formation in a CDM universe[1]. A possible solution was recently proposed by Crain et al. (2010, hereafter C10). They showed that disc, star-forming galaxies in the cosmological hydrodynamic simulations of the GALAXIES-INTERGALACTIC MEDIUM INTERACTION CALCULATION (GIMIC, Crain et al. 2009) do, in fact, develop the kind of gaseous coronae predicted by WF91, but with an associated X-ray emission that is one to two orders of magnitude fainter than the WF91 prediction. The main reason for this is that, contrary to the assumption of WF91, the density profile of the hot gas does not follow the density profile of the dark matter. Instead, it is much less centrally concentrated as a result of energy injection from SNe at the peak of the star formation activity, $z \sim 1-3$. This raises the entropy of the gas, both by driving outflows that shock the gas to high temperatures and by ejecting low-entropy gas from the progenitor haloes.

C10 showed that although the X-ray emission around disc galaxies in GIMIC comes predominatly from an extended quasi-hydrostatic corona heated by shocks and gravitational contraction, the galaxies reproduce the observed scaling of the soft X-ray luminosity with K-band luminosity, disc rotation velocity and star formation rate. The presence of the latter correlation – which arises because both the X-ray luminosity and the star formation rate scale with halo mass – contradicts the main source of evidence in favour of the view that the X-ray emission observed around real disc galaxies must be directly associated with star formation (perhaps through a galactic wind or fountain). The low surface brightness of coronal gas renders it difficult to detect with *Chandra* and *XMM-Newton*, making it an ideal target for future facilities such *Astro-H* or the *International X-Ray Observatory* (*IXO*). Sensitive, high-resolution spectroscopy with these facilities has the potential to verify directly whether coronal gas is quasi-hydrostatic or outflowing.

In the meantime, it is interesting to explore another consequence of the WF91 framework, namely that the properties of the hot coronal gas should be broadly independent of the morphological characteristics of the galaxy. Thus, just as bright disc galaxies, bright elliptical galaxies are also expected to have extended coronae of X-ray emitting hot gas. Furthermore, since ellipticals are dominated by old stellar populations and have little ongoing star formation, the view that most of the X-ray emission comes from outflowing winds triggered by SNe-II can be readily ruled out (for a review, see Mathews & Brighenti 2003). Active galactic nuclei (AGN) are not thought to be important in the production of X-ray emission from $L_\star$ ellipticals (David et al. 2006).

In this paper we explore the properties of diffuse X-ray emission in $L_\star$ galaxies of different optical morphologies. Recent data from *Chandra* and *XMM-Newton* provide relatively large samples of X-ray luminosities and temperatures (or upper limits) for normal (i.e. non-interacting, relatively isolated) $L_\star$ disc and elliptical galaxies. The observational samples that we analyse in this paper are introduced in § 2. In § 3, we present comparisons of derived X-ray scalings for discs and ellipticals. In § 4, we propose that the hot coronal gas in disc and elliptical galaxies has a common origin – accretion onto a shock-heated quasi-hydrostatic hot corona – and explore the consequences of this proposal. We include a short appendix, in which we show that ejecta from SNe-Ia and SNe-II are unlikely to be the source of the hot coronal gas in galaxies of any morphological type.

2 X-RAY DATA

We first introduce the sample of galaxies that we use in this study, which are taken from previously published X-ray studies. As the X-ray flux from point sources can be comparable to (or even dominate) that from the hot gas of normal galaxies, high quality X-ray observations are required to determine the emission that truly originates from the coronal gas. For this reason, we have limited our compilation of galaxies to those that have *Chandra* and/or *XMM-Newton* observations reported in the literature. We describe the sample below, with a brief discussion of how the X-ray luminosity of the hot gas was measured in each case.

2.1 Elliptical galaxies

Our sample of elliptical galaxies with X-ray luminosities and temperatures is taken from two studies: David et al. (2006, hereafter D06) and Mulchaey & Jeltema (2010, hereafter MJ10). The D06 sample is comprised of 18 low optical luminosity ($L_{\rm B} \lesssim 3 \times 10^{10} L_{{\rm B},\odot}$) field elliptical galaxies observed with *Chandra*, drawn from a larger sample of early type galaxies with *Chandra* archival data (C. Jones, in prep.). The non-thermal X-ray emission from low-mass X-ray binaries (LMXBs) was accounted for in D06 by spatial excision of bright sources and spectral modelling (using a power-law component) of unresolved sources. MJ10 selected their sample of 23 nearby field early type galaxies from previously published X-ray catalogues (e.g. O'Sullivan et al. 2001). Approximately half of their sample was observed with *Chandra* and the other half with *XMM-Newton*, with several galaxies having data from both satellites. The MJ10 sample nicely complements that of D06, as it is comprised of relatively bright systems ($L_{\rm K} \gtrsim 10^{11} L_{{\rm K},\odot}$). In similar fashion to D06, MJ10 accounted for non-thermal emission from LMXBs through the inclusion of a power-law component in their spectral modelling.

While it is possible to remove the contribution from unresolved non-thermal sources on the basis of their spectra (which can be can be differentiated from thermal spectra if there are sufficient photons), removal of X-ray emission from a potential *thermal* point source population is more difficult. An good example is the emission originating from the so-called Galactic Ridge. This emission had previously been believed to come from hot gas, since its spectrum is consistent with an optically-thin plasma (with $T \sim 10^{7-8}$ K) and even displays a prominent iron K line. However, Revnivtsev et al. (2006, 2008) pointed out that the X-ray surface brightness traces almost perfectly the K-band surface brightness in that region of the Galaxy, as is also the case in external galaxies such as NGC 3379 (which is part of the D06 sample). Revnivtsev et al. (2009) used a 1 Ms *Chandra* exposure to show that, indeed, most of

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[1] The so-called "cold flows" advocated, for example, by Birnboim & Dekel (2003) are subdominant for the halo masses and redshifts of interest here.

the Galactic Ridge emission originates from individual faint point sources, specifically accreting white dwarfs and cataclysmic variable stars.

At present it is not possible to remove directly the contribution of faint thermal point sources to the X-ray luminosity in the samples of D06 and MJ10. However, we can use the tight correspondence, reported by Revnivtsev et al. (2008), between the X-ray luminosity of these faint sources and the K-band luminosity, to estimate their importance. We do this below, in § 3.1. We conclude from this comparison that the contribution from faint thermal point sources is potentially significant for 5 or 6 faint ellipticals from D06, and for 3 ellipticals from MJ10.

2.2 Disc galaxies

Unfortunately, there are no large, homogeneously analysed samples of normal disc galaxies observed with *Chandra* or *XMM-Newton*, analogous to those of D06 and MJ10 for ellipticals. This may, in part, be due to the commonly held belief (arising from *ROSAT*'s low detection rate of coronal gas) that disc galaxies do not possess X-ray-luminous coronae, suggesting that there is little point in obtaining X-ray observations of such systems for the purpose of studying hot gas. In spite of this, there is a growing body of work on small samples of disc galaxies that shows that these galaxies do indeed have detectable diffuse, coronal emission. As we will show below, the properties of the hot coronae of disc galaxies are remarkably similar to those of ellipticals of the same mass.

Our heterogeneous sample of disc galaxies is taken from a number of studies, including Strickland et al. (2004, hereafter Str04), Wang (2005, hereafter W05), Tüllmann et al. (2006, hereafter T06), Li et al. (2007, hereafter L07), Owen & Warwick (2009, hereafter OW09), Sun et al. (2007, hereafter Sun07), Jeltema et al. (2008, hereafter J08), and Rasmussen et al. (2009, hereafter R09). Str04, W05, T06, L07, and R09 all studied *edge-on* disc galaxies. Str04 used *Chandra* to observe a sample of 10 star-forming galaxies, 7 of which are classified as starbursts. W05 report on *Chandra* observations of 7 'normal' star-forming galaxies. T06 observed with *XMM-Newton* a sample of 9 normal star-forming disc galaxies. L07 observed the nearly edge-on Sombrero galaxy (M104) with *Chandra*. R09 observed two quiescent edge-on disc galaxies with *Chandra*, but found no significant diffuse emission away from the disc. For all these studies we use only the reported *extra-planar* X-ray luminosity (or upper limits) of the hot gas (see Table 9 of Str04, Table 1 of W05, and Table 9 of T06).

Since we exclude the luminosity from the region that is spatially coincident with the disc, there is no significant contribution from faint thermal point sources to the X-ray luminosities of disc galaxies that we analyse here. OW09, however, observed a sample of 6 nearby *face-on* disc galaxies with *XMM-Newton*. For these systems emission from faint thermal point sources could be a contaminant but, as we show below, the expected contribution from these sources is much smaller than the total measured X-ray luminosities.

Finally, S07 and J08 reported *Chandra* X-ray detections (and upper limits) of optically luminous early and late type galaxies in several nearby galaxy groups and clusters. We have elected to use their late type galaxies to complement our relatively small sample, in spite of the fact that the luminosity of these systems could be influenced by the group/cluster environment (e.g., if ram pressure strips some of the hot gas). In a forthcoming study (McCarthy et al. *in prep*), however, we show (using cosmological hydrodynamical simulations) that, for those galaxies that are not completely stripped of their gas, the X-ray luminosity is largely unchanged by ram pressure stripping. This is because the X-ray luminosity is very centrally concentrated so the brightest gas is the very last to be stripped.

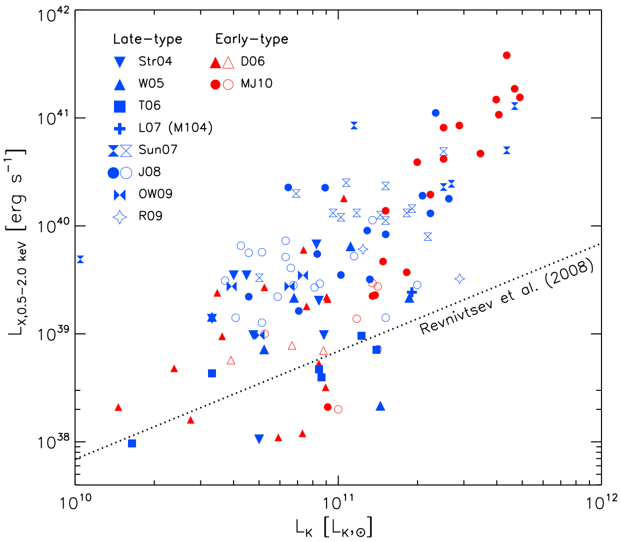

Figure 1. The 0.5-2.0 keV X-ray luminosity of the hot gas as a function of K-band luminosity, for a sample of disc (blue symbols) and elliptical (red symbols) galaxies drawn from a number of studies (see legend and text). For disc galaxies, we quote extra-planar X-ray luminosities where possible and, for both morphological classes, X-ray luminosities have been corrected for non-thermal point source contributions. Filled symbols denote X-ray detections, open symbols denote upper limits. Corresponding K-band luminosities were extracted from the online 2MASS database. The dotted line represents the potential contribution from faint thermal point sources (see text). Remarkably, the two morphological types exhibit broadly the same slope, normalisation and scatter in the $L_X - L_K$ relation.

3 COMPARISON OF THE OBSERVED X-RAY SCALINGS OF DISC AND ELLIPTICAL GALAXIES

In this section, we examine correlations between the X-ray luminosity of the hot gas and the near-infrared (K-band) luminosity of the galaxy, as well as the temperature of the hot gas, inferred from X-ray spectroscopy.

3.1 The $L_X - L_K$ relation of disc and elliptical galaxies

We begin by examining, as a function of stellar morphology, the scaling of the diffuse soft X-ray luminosity with the K-band luminosity, L_K, which is a good proxy for stellar mass. We have converted X-ray luminosities quoted in other passbands into the 0.5-2.0 keV band using the PIMMS tool[2] (Mukai 1993). K-band luminosities were extracted from the IPAC online database for the Two Micron All-Sky Survey (2MASS, Skrutskie et al. 2006).

Fig. 1 shows the coronal soft X-ray luminosity as a function of K-band luminosity for our samples of disc (blue symbols) and elliptical (red symbols) galaxies. Systems with X-ray detections are denoted by filled symbols, whilst upper limits are denoted by open symbols. Remarkably, the two morphological classes populate the

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[2] http://heasarc.nasa.gov/docs/software/tools/pimms.html

L_X-L_K plane in a very similar way: the relation between these two properties has similar slope, normalisation and scatter for both classes. We conclude that, for fixed stellar mass, the X-ray luminosity of hot coronae is unrelated to the morphology of the host galaxy.

Since the X-ray emission has been explicitly corrected for non-thermal point-source contamination, the correlation in Fig. 1 is not a reflection of the linear correlation between *total* X-ray luminosity (i.e. uncorrected for point sources) and optical luminosity that is known to exist for low optical luminosity ellipticals (O'Sullivan et al. 2001). Nor is the correlation driven by a contribution from faint thermal point sources (e.g. accreting white dwarfs and cataclysmic variable stars) that cannot be removed spectrally, since only a small number of faint ellipticals in our sample have coronal luminosities that are comparable to, or less than, the integrated luminosity of thermal point sources inferred from the relation of Revnivtsev et al. (2008, see dotted line in Fig. 1). Several of our faint disc galaxies also lie below this relation but, as discussed in § 2.2, the luminosities from Str04, W05, T06, L07, and R09 are attributed exclusively to *extra-planar* emission, and are therefore unlikely to be contaminated by point sources.

The correlation between the optical and X-ray luminosities of disc and elliptical galaxies has been explored previously (e.g. Fabbiano 1989). However, such studies analysed data from the *Einstein* and *ROSAT* telescopes, which i) lacked the sensitivity to detect diffuse X-ray emission in low (optical) luminosity galaxies and ii) lacked the spatial and spectral resolution to enable the subtraction of point-source contributions to the X-ray flux. As a result, those studies were not able to find the similarity in the correlation between the *coronal* X-ray luminosity and stellar mass for disc and elliptical galaxies that we have uncovered here.

3.2 The $L_X - T_X$ relation of disc and elliptical galaxies

The similarity of the $L_X - L_K$ relations for disc and elliptical galaxies revealed in Fig. 1 indicates that the X-ray luminosity of hot coronal gas does not depend on the morphology of the visible galaxy for systems of fixed mass, insofar as the K-band luminosity reflects the stellar mass and the stellar mass reflects the total mass. It is conceivable, however, that normal disc and elliptical galaxies could have different stellar mass fractions and that the similarity of their $L_X - L_K$ relations could therefore be the result of some 'conspiracy' or coincidence. For example, ellipticals could be more X-ray luminous at a fixed total mass, but also have higher stellar mass fractions. We can rule out any potential conspiracy of this sort by examining the $L_X - T_X$ relation. The temperature of the gas is a measure of the depth of the total (stars+gas+dark matter) potential well of the galaxy (e.g. Voit et al. 2002), so long as the gas is relatively close to hydrostatic equilibrium. This is a reasonable assumption, since if the gas were far from hydrostatic equilibrium, it would quickly collapse or leave the system.

Fig. 2 shows the X-ray luminosity as a function of the hot gas spectral temperature for those galaxies from the sample presented in Fig. 1 that have temperature estimates. Note, however, that we have excluded those galaxies from the samples of D06 and MJ10 for which the inferred X-ray luminosity lies below the estimated contribution from faint thermal point sources (see discussion in § 2.1 and 2.2). For reference, we also include measurements of galaxy groups, taken from the studies of Helsdon & Ponman (2000) and Mulchaey et al. (2003), galaxy clusters from Horner (2001), and of the Milky Way (Henley et al. 2010) and M31 (Liu et al. 2010).

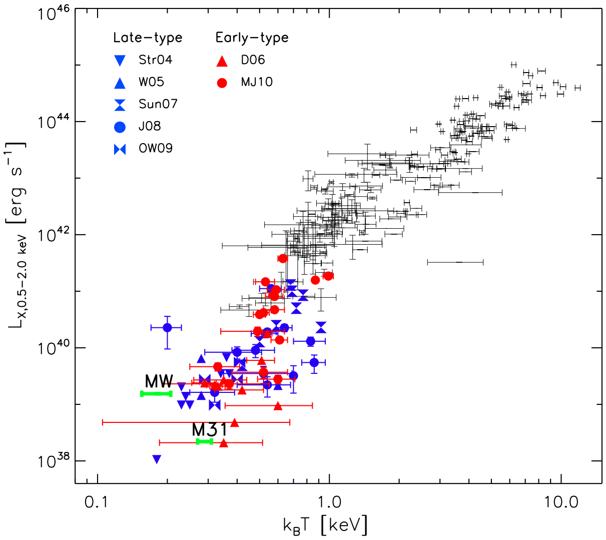

Figure 2. The X-ray luminosity-temperature relation in the 0.5-2.0 keV band. We plot those galaxies from the sample shown in Fig. 1 that i) have a spectroscopic measurement of the coronal temperature and ii) in the case of ellipticals, have a total X-ray luminosity above the expected thermal point source contribution. Also plotted are measurements for the Milky Way (Henley et al. 2010) and M31 (Liu et al. 2010), shown as green error bars, the galaxy group samples of Helsdon & Ponman (2000) and Mulchaey et al. (2003), and the galaxy cluster sample of Horner (2001), both shown as black error bars. Note the break in the $L_X - T_X$ relation at ~ 1 keV. As was the case for the $L_X - L_K$ relation of Fig. 1, disc and elliptical galaxies follow the same relation.

We find, once again, the remarkable result that disc and elliptical galaxies follow the same relation. This provides a strong argument against the notion that an astrophysical coincidence or conspiracy is responsible for the similarity of the $L_X - L_K$ relations for the two morphological types. The relation shown in Fig. 2 reinforces our previous conclusion that the X-ray properties of hot coronal gas do not depend on stellar morphology. It is also interesting to note that the addition of our galaxy samples to the well-known $L_X - T_X$ relation obeyed by galaxy groups and galaxy clusters forms a broken power-law with the break at approximately 1 keV. We discuss this intriguing result further in § 4.

4 INTERPRETATION AND DISCUSSION

The presence of hot, X-ray luminous coronae around present day $L_\star$ galaxies is a fundamental prediction of galaxy formation theory in a cold dark matter cosmology. Indeed, such hot coronae arise in both analytic and numerical models (e.g. WF91, C10, see also Benson et al. 2000; Toft et al. 2002; Rasmussen et al. 2009). They form as gas accreting onto growing dark matter halos is shock-heated at the virial radius and adiabatically compressed. In sufficiently large halos, the cooling time is longer than the infall time and the gas forms a quasi-hydrostatic atmosphere around the galaxy[3]. As it slowly cools, radiating its energy in the soft X-ray band, the gas,

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[3] When the cooling time is short, galaxies can accrete gas without it being shock-heated at the virial radius. However, C10 showed, using the GIMIC simulations, that these "cold flows," (e.g. Birnboim & Dekel 2003; Kereš et al. 2005) provide only a small fraction of the ongoing gas accretion onto $L_\star$ galaxies today.

tidally torqued earlier on, settles onto a disc. It is subsequently contaminated by galactic winds ejected from the forming galaxy but, according to the simulations of C10, the contamination is small. The temperature of the gas is determined by the gravitational potential of the halo and, for present day $L_\star$ galaxies, it is of the order of 10^6 K. Thus, a strong correlation is established between coronal X-ray luminosity and halo mass. In the absence of significant differences between the hot gas fractions of disc and elliptical galaxies, this relation should not be sensitive to the optical morphology of the galaxy.

In this study, we have obtained strong observational support for this general picture. Firstly, we report a correlation between coronal X-ray luminosity and stellar mass (as measured by K-band luminosity) that has essentially the same normalisation, slope and scatter for disc and elliptical galaxies. Secondly, we report a correlation between coronal X-ray luminosity and mass (as measured by the spectral temperature of the plasma) that is also similar for both types of galaxy.

We stress that the correlations we have found involve the *coronal* gas. They are not affected by point sources since the X-ray emission has been explicitly corrected for non-thermal point source contamination and, with a few exceptions, the X-ray luminosities are much higher than the contribution expected from unresolved thermal point sources (such as accreting white dwarfs and cataclysmic variables) according to the relation derived by Revnivtsev et al. (2008). Thus, the correlations we have found are qualitatively and quantitatively different from those previously obtained between *total* X-ray luminosity (including stellar contributions) and optical properties as a function of galaxy morphology (e.g. Fabbiano 1989).

While according to theory and simulations the coronal gas in both discs and ellipticals is predominantly primordial, it is often thought that the source of coronal gas could be internal, namely gas ejected during stellar evolution and heated mostly by Type II SNe, in the case of discs, and by Type Ia SNe, in the case of ellipticals (e.g. Mathews & Brighenti 2003; Tüllmann et al. 2006). In this picture, it is difficult to understand why discs and ellipticals should have such similar $L_{\rm X} - L_{\rm K}$ and $L_{\rm X} - T_{\rm X}$ relations given that they have such different stellar populations and star formation rates. In the Appendix, we present analytic arguments, supported by observational evidence, that demonstrate the difficulty of establishing common $L_{\rm X} - L_{\rm K}$ and $L_{\rm X} - T_{\rm X}$ relations through such mechanism.

By contrast, in our picture in which the X-ray emission arises from coronal gas, the correlations between $L_{\rm X}$, $T_{\rm X}$ and K-band luminosity in present day $L_\star$ galaxies are easy to understand: they arise because all three quantities are proportional to halo mass. This is directly seen in the GIMIC simulations (Crain et al. 2009, C10), which also show how the scatter in the $L_{\rm X} - L_{\rm K}$ relation arises from the scatter in the $L_{\rm K}$-$M_{\rm vir}$ relation (see Fig. 6 of C10).

We remarked in § 3.2 that the extended $L_{\rm X} - T_{\rm X}$ relation, obtained by combining our sample of galaxies with data for galaxy groups and galaxy clusters (Helsdon & Ponman 2000; Mulchaey et al. 2003; Horner 2001), can be described by a broken power-law, with the break at $\sim 1\,$keV. A steepening of the $L_{\rm X} - T_{\rm X}$ relation at galaxy group temperatures has been known for some time (e.g. Helsdon & Ponman 2000), but we now see that the steeper slope extends seamlessly down to normal galaxies[4]. Extensive theoretical work, extending back over a decade, has sought to explain the origin of the steepening of the relation at group temperatures (or masses). Simple preheating models, in which the entropy of the proto-intragroup and proto-intracluster media is uniformly raised by some unspecified feedback source, are able to reproduce the break (e.g. Balogh et al. 1999).

A qualitatively similar relation to the one shown in Fig. 2, with a break at $0.7\,$keV, was obtained by Davé et al. (2002) in a cosmological hydrodynamic simulation including radiative cooling and star formation. These authors identified two causes for the break: i) a reduction in the X-ray luminous gas density in haloes below the break scale due to the removal of coronal gas, and ii) a systematic variation of the density structure of the corona with halo mass. As discussed in § 1, a reduction in the central gas density is one of the reasons why the gas coronae of $L_\star$ galaxies in the GIMIC simulations are far less luminous than expected by WF91. On the scale of galaxies, however, this reduction is primarily effected by feedback from Type II SNe, rather than by cooling and star-formation.

A common origin for the hot coronal gas in $L_\star$ disc and elliptical galaxies raises an interesting question: if the X-ray properties of the coronae are so similar, why are the star formation properties of discs and ellipticals so different? Although we plan to address this conundrum using simulations such as GIMIC, it is tempting to relate the differences to the processes that turn discs into present day ellipticals. According to Parry et al. (2009), the most common processes are minor mergers and disc instabilities (except for bright ellipticals which form predominantly by mergers) occuring at $z \lesssim 1$. These events are likely to be accompanied by starbursts that produce a relatively small number of stars but that can temporarily disrupt the cooling flow from the corona. The flow is eventually restored but only a relatively a small amount of gas has had time to cool by the present. A mechanism of this sort might explain the blue discs around bulge-dominated galaxies detected using *GALEX* data by Kauffmann et al. (2007) and the low-level star formation inferred in most ellipticals by Kaviraj et al. (2008). Searches for cold gas with millimetre and radio wave facilities (e.g. Oosterloo et al. 2007; Combes et al. 2007; Krips et al. 2010) would provide a useful test of this picture.

Our conclusions are based on the analysis of a small and heterogeneous sample, particularly in the case of disc galaxies. Homogeneous samples of *optically* selected, normal disc and elliptical galaxies can easily be extracted from surveys such as the SDSS and their X-ray properties determined from deep X-ray observations that are possible with *Chandra* and *XMM-Newton*. Such a programme would set new and valuable constraints on theories of galaxy formation.

ACKNOWLEDGEMENTS

We thank John Mulchaey for supplying us with unpublished temperature measurements. RAC acknowledges the hospitality of the Institute for Computational Cosmology, Durham, and the Institute of Astromomy, Cambridge, where part of this work was carried out. RAC is supported by the Australian Research Council through a Discovery Project grant. IGM acknowledges support from a Kavli

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[4] The break in the $L_{\rm X} - T_{\rm X}$ relation apparent in Fig. 2 is not due to the use of soft $(0.5 - 2.0\,\text{keV})$, rather than bolometric, X-ray luminosities. We have checked this by constructing a version of Fig. 2 for bolometric luminosities estimated assuming a bolometric correction for an APEC plasma model of the observed temperature and metallicity. The bolometric relation still shows a prominent break at $\sim 1\,$keV, and both galaxies and galaxy groups exhibit similarly steep relations.

Institute Fellowship at the University of Cambridge. CSF acknowledges a Royal Society Wolfson Research Merit award. This study makes use of data products from the Two Micron All Sky Survey (2MASS) and the Infrared Astronomical Satellite (*IRAS*), obtained from archives hosted by IPAC.

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APPENDIX A: SUPERNOVAE HEATING AND HOT GASEOUS CORONAE

We briefly investigate the role of internal SNe heating in the production of hot circumgalactic gas around $L_\star$ galaxies. We first consider star-forming disc galaxies in which Type II SNe dominate the energy injection rate.

There are some galaxies in which extra-planar X-ray emission is clearly being powered by an outflow driven by Type II SNe, for example, where there is co-spatial optical line emission such as Hα (e.g., Str04). In the most dramatic examples such as M82, biconical X-ray contours (Strickland & Heckman 2007) are the tell-tale sign of strong nuclear outflows (for a review, see Veilleux et al. 2005).

However, the fraction of detectable extra-planar X-ray emission associated with outflows is uncertain.

C10 observed that the $L_{\rm X} - \dot{M}_\star$ correlation is signficantly weakened when disc galaxies with low X-ray luminosity and low star formation rate are included. As shown in their Fig. 5, observations of star-forming galaxies exhibit considerable scatter in the $L_{\rm X} - \dot{M}_\star$ plane. If the hot gas associated with disc galaxies were exclusively heated by Type II SNe, a stronger correlation between $L_{\rm X}$ and $\dot{M}_\star$ would be expected, because of the prompt detonation of Type II SNe after star-formation episodes ($\lesssim 30\,$Myr) and the relatively short central cooling time of the corona ($t_{\rm cool}^{\rm corona} \ll t_{\rm H}$). Morever, as argued by C10, even a strong correlation between $L_{\rm X}$ and $\dot{M}_\star$ does not necessarily imply that the hot gas is related to SNe since (to first order) both quantities are expected to scale with the mass of the galaxy's dark matter halo.

In present-day ellipticals, with little or no ongoing star formation, Type Ia SNe are the dominant energy source. Integrating over the lifetime of the observed stellar populations, it would seem that the energy budget from Type Ia SNe is sufficient to maintain a quasi-hydrostatic hot corona (Mathews & Baker 1971; Loewenstein & Mathews 1987; Brighenti & Mathews 1999). In § 4, however, we suggested that the similarity of the $L_{\rm X} - L_{\rm K}$ and $L_{\rm X} - T_{\rm X}$ relations for disc and elliptical galaxies argues against the hypothesis that the coronae of the two types of galaxy are produced by different mechanisms.

Let us set aside for the moment the argument that the scatter in the $L_{\rm X} - \dot{M}_\star$ relation of disc galaxies is difficult to reconcile with an internal heating origin for hot coronae. For both morphological types to produce the same X-ray luminosity at fixed stellar mass and fixed halo mass, it is necessary that the energy injection rate at the present day, from Type II SNe in the case of disc galaxies and from Type Ia SNe in the case of ellipticals galaxies be comparable. This requires uncomfortable fine-tuning.

Using empirical constraints, we can estimate whether such a coincidence is possible. Adopting the Chabrier (2003) stellar initial mass function (IMF), spanning the range 0.1-100 $\rm M_\odot$, let us assume that all stars with masses between 8 and 100 $\rm M_\odot$ end their lives as Type II SNe, and that 2.5 percent of stars with masses between 3 and 8 $\rm M_\odot$ end their lives as Type Ia SNe (see Fig. A6 of Wiersma et al. 2009). Each SN, of either type, generates a kinetic energy, $E_{\rm SN}$, which we will assume to be $\sim 10^{51}$ erg. In the case of Type II SNe, this energy is liberated on a timescale much shorter than $\min(t_{\rm dyn}, t_{\rm cool})$, and the rate of energy injection from these events can thus be approximated as

$$\dot{E}_{\rm SNII}(M_\star) = E_{\rm SN}\dot{M}_\star(M_\star)\int_{8\,\rm M_\odot}^{100\,\rm M_\odot}\phi(m){\rm d}m, \tag{A1}$$

where $\phi(m){\rm d}m$ is the IMF. A reasonable estimate of $\dot{M}_\star(M_\star)$ can be obtained from a simple power-law fit to the $\dot{M}_\star - M_\star$ plane of SDSS star-forming galaxies derived by Brinchmann et al. (2004, their Fig. 17). We therefore adopt

$$\log_{10}\dot{M}_\star[\rm M_\odot\,yr^{-1}] = -5.865 + 0.615\log_{10}M_\star[\rm M_\odot]. \tag{A2}$$

Since Type Ia SNe are thought to result from binary evolution, a single stellar population will produce Type Ia SNe over an extended period. The lifetimes of the progenitors remain poorly understood (see e.g. Podsiadlowski et al. 2008), requiring that the number of detonations per unit time be modelled with a theoretical or an empirically-motivated delay function, $\xi(t)$, which is normalised such that $\int_0^\infty \xi(t){\rm d}t = 1$. Hence, the specific number of SNIa over some time interval is,

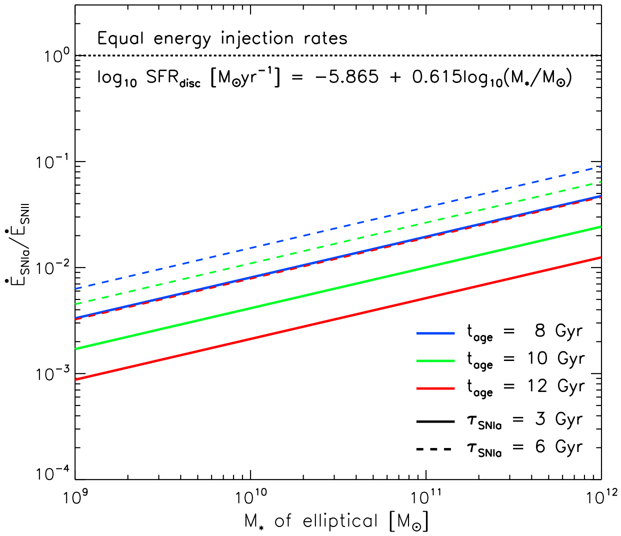

Figure A1. The ratio of instantaneous energy injection rates from Type Ia SNe, derived from an evolved stellar population within an elliptical galaxy, and Type II SNe from ongoing star formation at the average rate observed in SDSS galaxies (Brinchmann et al. 2004). Different ages for the dominant stellar population in the elliptical galaxy $(8, 10, 12\,{\rm Gyr})$ are shown by the coloured lines. The solid and dotted lines are for an assumed characteristic delay time for Type Ia SNe of 3 Gyr and 6 Gyr respectively.

$$n_{\rm SNIa}(t : t+\Delta t) = \nu\int_t^{t+\Delta t}\xi(t'){\rm d}t', \tag{A3}$$

where ν is the number of Type Ia SNe per unit stellar mass formed that will ever occur. Recall that we adopt a value of 2.5 percent of all stars between 3 and 8 $\rm M_\odot$, such that

$$\nu = 0.025\int_{3\,\rm M_\odot}^{8\,\rm M_\odot}\phi(m){\rm d}m. \tag{A4}$$

We assume a simple e-folding delay function of the form,

$$\xi(t) = \frac{e^{-t/\tau}}{\tau}, \tag{A5}$$

where τ is the characteristic delay time for which we take a fiducial value of 3 Gyr, which was shown by Wiersma et al. (2009, see their Fig. A6) to reproduce, in cosmological simulations, the observed cosmic Type Ia SN rate (e.g. Cappellaro et al. 1999; Hardin et al. 2000; Pain et al. 2002; Madgwick et al. 2003; Tonry et al. 2003; Blanc et al. 2004; Dahlen et al. 2004; Barris & Tonry 2006; Neill et al. 2006; Poznanski et al. 2007; Kuznetsova et al. 2008). For simplicity, we assume the spread of Type Ia ages contributing at any given time is $\ll \tau$. Hence

$$\dot{E}_{\rm SNIa}(M_\star) = \nu E_{\rm SN}M_\star\int_{t_{\rm age}}^{t_{\rm age}+{\rm d}t}\frac{e^{-t'/\tau}}{\tau}\frac{{\rm d}t'}{{\rm d}t}, \tag{A6}$$

Within observational constraints, we have some flexibility in the assumed age of the dominant stellar population in an elliptical galaxy, $t_{\rm age}$, so in Fig. A1 we adopt three values (8, 10 and 12 Gyr) and plot the ratio of the energy injection rates from Type Ia SNe from these populations to that of Type II SNe (Eqn. A1), as a function of the galaxy's stellar mass. The solid coloured lines show that, for reasonable choices of the age of the elliptical galaxy population and our well-motivated (but uncertain) choice of the e-folding timescale (3 Gyr), the energy injection rate due to Type II SNe is always $\sim 1-2$ orders of magnitude greater than that due to the Type Ia SNe of an evolved population.

The only reasonable freedom we have to vary the parameters of this simple model is to modify the poorly constrained value of τ. A longer delay timescale shifts a greater fraction of the energy liberated by Type Ia SNe to later times so, for reasonable elliptical galaxy formation histories, a greater value of τ will increase $\dot{E}_{\rm SNIa}$ at $z = 0$. We therefore also consider the bracketing case of doubling the delay timescale (to $6\ {\rm Gyr}$), shown in Fig. A1 with dashed lines. Clearly, making this conservative assumption does not alter our main result. We therefore conclude that it is not possible to accomodate a model in which the similar X-ray luminosities of normal disc-dominated and elliptical galaxies at fixed stellar mass stem from the ongoing injection of energy from these two different internal sources.