

The X-ray halo of an extremely luminous LSB disk galaxy

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Final Technical Report and Summary of Research

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The purpose of this project is to obtain XMM/Newton observations of the giant low surface brightness (LSB) disk galaxy Malin 2 (LSBC F568-6). This galaxy is unusual and interesting because even though it is low in surface brightness, it is very large and luminous, with a total optical R luminosity of $8.3L_*$ (Pickering *et al.* 1997, AJ, 114, 1858). Its luminosity and scale length are more comparable to giant elliptical galaxies or even poor groups of galaxies than to typical spiral galaxies.

X-rays are frequently detected from halos of hot, $T \sim 10^7$ K gas surrounding giant ellipticals and galaxy groups. However, X-ray emission from spiral galaxies is weak, and consistent with the emission expected from X-ray sources associated with star formation, *e.g.* supernova remnants and LMXBs (Fabbiano *et al.* 1992, ApJS, 80, 531). Therefore, hot halo gas is not known to exist around disk galaxies. Early calculations of the expected X-ray halos of disk galaxies suggested that standard models of galaxy formation predict a substantial reservoir of hot gas around disk galaxies (Benson *et al.* 2000, MNRAS, 314, 557). But such gas would be fairly difficult to observe, since the virial temperature of a typical disk galaxy halo is $T \sim \text{few} \times 10^6$ K; the X-ray emission would be soft, hard to detect and easily absorbed.

We chose to observe a giant LSB disk galaxy because its mass and velocity scale σ approach that of giant ellipticals or poor groups. There are suggestions that giant LSBs could have formed from initial density fluctuations that were of the same size as those giving rise to ellipticals, but with higher spin, so that the final state is a rotating disk galaxy, in a way a “failed group” (Burstein *et al.* 1997, AJ, 114, 1365). If Malin 2 fell on the $L_X - \sigma$ and $T_X - \sigma$ relations of poor groups (Mulchaey & Zabludoff 1998, ApJ, 496, 73), its halo gas would be both luminous and hot enough to detect with XMM, predicting an X-ray luminosity $L_x \sim 2 \times 10^{42}$ erg/s, and an observed flux $f_x \sim 2.2 \times 10^{-13}$ erg s $^{-1}$ cm $^{-2}$ (0.5-2.0 keV).

Our reductions to date of the XMM data show that this level of flux is not achieved. We detected X-ray emission from Malin 2 with the EPIC camera on XMM, but the flux in band 2 is $f_x \sim 1 - 2 \times 10^{-14}$ erg s⁻¹ cm⁻², or 10 times lower than predicted from the group $L_X - \sigma$ relation. The emission is also not as extended as a hot halo should be. It is likely that at least some of this X-ray emission comes from the galaxy's disk; the flux detected is about a factor ~ 2 higher than predicted from the $L_X - L_B$ relation for disk galaxies (Fabbiano *et al.* 1992). It is also possible that there is emission from an AGN, as there appear to be X-ray detections in the harder bands, though these are marginal due to the relative sensitivity of the cameras.

We are continuing to refine our upper limit on emission from halo gas in Malin 2. The upper limit is, of course, below the detected flux, but is made more difficult to quantify by the disk and possible AGN sources. We are also exploring spectral and spatial-size constraints to help separate the sources of emission.

On the theory side, more recent work on the X-ray halo luminosity from halo gas leftover from galaxy formation has lowered the prediction for disk galaxies (*e.g.* Toft *et al.* 2002, MNRAS, 335, 799). While our upper limit is well below the original prediction, refinements in model have moved the theoretical goalposts, so that the observation may be consistent with newer models.

A recent theoretical development, which our observations of Malin 2 appear to support, is that a substantial amount of mass can be accreted onto galaxies without being heated at a virial shock. The previous standard theory was that gas accreting into a halo hits a virial shock and is heated to high temperatures, which could produce X-ray halos in massive galaxies. Recent models show that “smooth accretion” of matter bypasses the virial shocking (Murali *et al.* 2002, ApJ, 571, 1; Birnboim & Dekel 2003, MNRAS, 345, 349). Additionally, new hydrodynamical simulations of galaxy mergers by UCSC graduate student T.J. Cox show that hot gas halos can be created by gas blown out from the merger, taking up orbital energy of the merging galaxies (Cox *et al.* 2004, ApJ, 607, L87).

If mergers rather than virial shocking are the origin of hot gas halos, the existence of an X-ray halo should depend more on past merger activity than halo mass. Then it makes sense that elliptical galaxies and poor groups with ellipticals, which are probably formed in mergers, have X-ray gas halos; while a giant, quiescent LSB disk galaxy like Malin 2, which has never suffered a major merger, does not have an X-ray halo. While both the observational expectations and theoretical models have changed since we began this project, which has forced us to re-evaluate the goals, we are pressing forward to firm up the observations and put them in context of the current models for X-ray halos of massive galaxies.