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THE SOFT X-RAY HALO OF THE SPIRAL GALAXY NGC4631

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ABSTRACT

We present ROSAT PSPC observations of the close to edge-on spiral galaxy NGC4631. This vigorously star forming galaxy shows extented X-ray emission perpendicular to the plane, out to about 6 to 8 kpc. The spatial extent is largest at soft X-ray energies. The total X-ray luminosity of hot gas can be easily supplied by star formation in the disk, and it is likely that the halo is due to outflow of hot gas from the inner disk. Spectral analysis of the X-ray data shows that part of the halo emission may be quite cool, well below 10^6K. We briefly discuss implications of these results.

1. Introduction

Ever since Spitzer (1956) predicted that halos of spiral galaxies might contain hot gas, this component of the interstellar medium (ISM) has stimulated much interest. Models of the interaction of supernovae with the ISM (Cox & Smith 1974, McKee & Ostriker 1977), and of the disk-halo interface (*e.g.* Bregman 1980, Norman & Ikeuchi 1989) have demonstrated that it is quite likely for such a hot component to exist; the surprising result is actually that it has been quite difficult to find it! (*e.g.* Fabbiano 1989, Fabbiano & Trinchieri 1987). NGC4631, a close to edge-on Sc spiral galaxy, may be the most likely target for finding a hot halo. It has vigorous star formation, as judged from its far-infrared luminosity (Rice *et al.* 1988) and its extensive radio halo (*e.g.* Hummel & Dettmar 1990). Its central 4 kpc of the disk shows a few long Hα filaments, indicative of disk-halo interaction, and possibly a thick diffuse ionized gas layer (Rand *et al.* 1992, Walterbos *et al.* 1993, 1994). In addition, the galaxy is only 7.5 Mpc distant, and its high Galactic latitude implies a low foreground HI column. The latter is crucial for the detection of X-rays below 0.4 keV, the range where hot gas is expected to emit most of its energy. However, NGC4631 may not be a proto-typical late-type spiral because it is interacting with two neighboring galaxies, producing extensive HI tidal tails (Rand & van der Hulst 1993), a radio halo, and enhanced star formation in the disk.

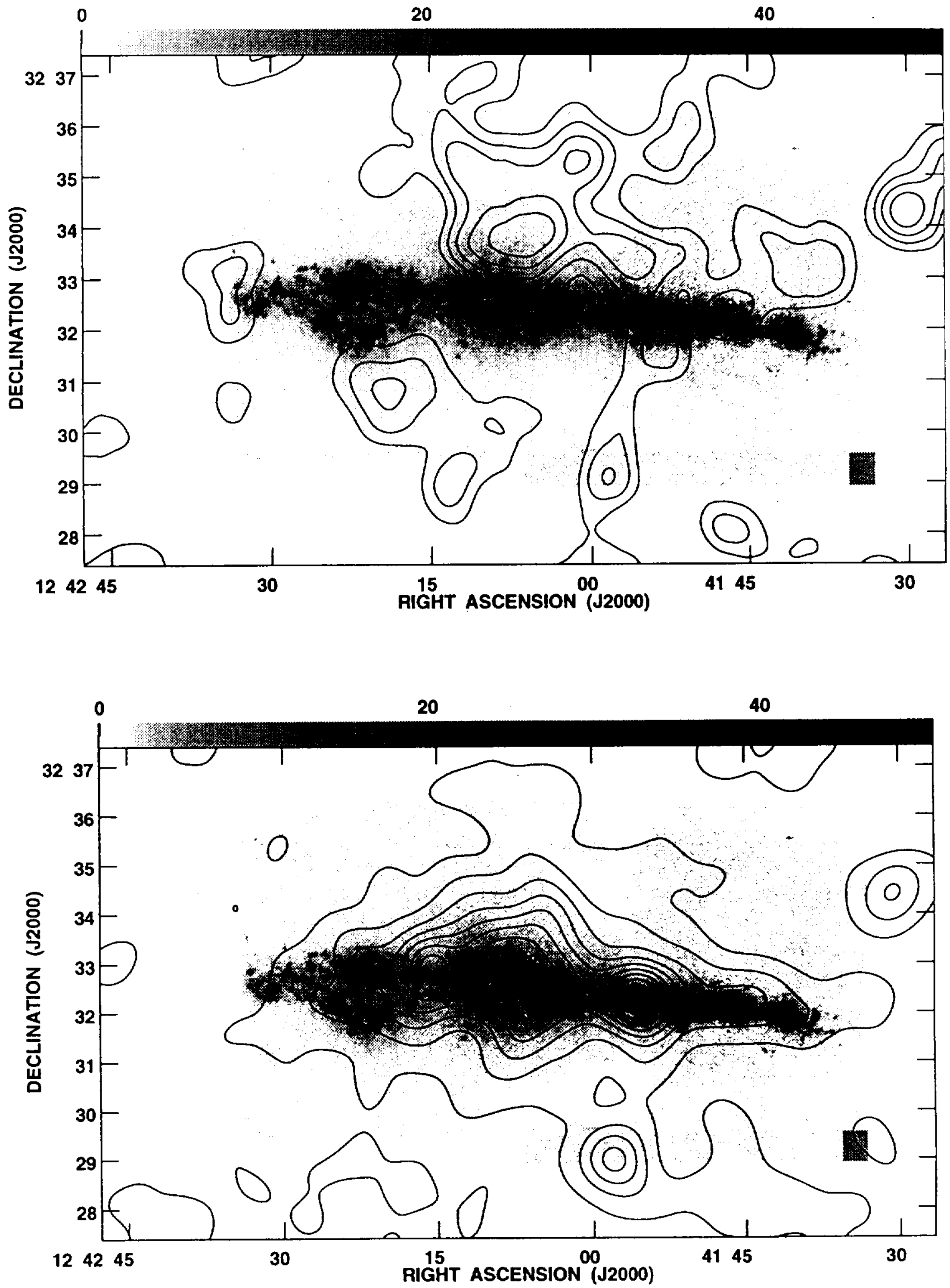

Figure 1. (Top) PSPC image of NGC4631 in the range 0.2-0.4 keV, superposed on an Halpha image (grey scale; note that the spatial alignment is still somewhat uncertain). Contours at 1, 2, 3, 4, and 5 (times 10(-6) counts/sec/pix) above background. (Bottom) The X-ray emission in the range 0.5-0.9 keV. Contours start at 2 and increase in steps of 2 (same units). One arcmin corresponds to 2.2 kpc.

2. Observations and results

We obtained a 23 ksec ROSAT PSPC observation of NGC4631, of which about 16 ksec was left after editing the data to delete periods with enhanced non-cosmic background count rates (Snowden *et al.* 1994). Complete results of this observation are presented by Wang *et al.* (1993) and by Walterbos *et al.* (1994). Data below 0.2 keV suffer badly from the electronic ghost problem, so these could not be used in creating images, but only in the spectral analysis. About 1200 counts were detected, 40% each from disk and halo, and 20% from a bright source west of the nucleus (Fig. 1) also seen by Einstein (Fabbiano & Trinchieri 1987). This source appears to coincide with a giant HI supershell (Wang *et al.* 1993). We plot X-ray contours over an Hα image in Fig. 1 for the soft and medium energy ranges. The X-ray emission, although weak (the highest contour in Fig. 1 (top) is about 5 sigma), is clearly extended above the disk, out to about 6 to 8 kpc. The extra-planar X-ray emission is prominent above the region of most intense Hα emission, near the "double worm" in Hα (Rand *et al.* 1992). The halo emission appears asymmetric, which may be intrinsic or due to the orientation at which we see NGC4631 (Walterbos *et al.* 1994). The medium energy image is also significantly extended in z-direction. The hard X-ray image (not shown) is more confined to the disk, which implies that the extra-planar *medium* X-rays are also likely due to hot gas, not to a population of hard X-ray binaries.

3. Spectral analysis and discussion

The spectra for the halo and disk regions are dramatically different (Fig. 2). A two-component fit to the disk spectrum is required, with one component hotter than 2.4×10^7K, probably due to hard X-ray binaries, and a cooler component of 3.5×10^6K, which we tentatively identify with hot gas in the disk. A foreground column of 10^{21} atoms cm^{-2} was assumed in the fit; the derived temperatures are not extremely sensitive to this assumption. The halo spectrum appears more complicated. A single temperature fit (middle panel) works well, and indicates a temperature of 2.8×10^6K, similar to the temperature of hot gas in the disk. The total luminosity for the hot gas (disk and halo) is about $5 - 7 \times 10^{39}$ erg s^{-1}. This luminosity is easily supplied by the energy input from supernovae, which amounts to about 10^{42} erg s^{-1}. The hard disk component contributes about 4×10^{39} erg s^{-1}.

Although the single temperature fit to the halo gas is appealing there may be a problem: the fit requires a very low foreground column of less than 3.3×10^{19} atoms cm^{-2}, which does not agree with the observed foreground HI column of 1.2×10^{20} atoms cm^{-2}. There is likely also a substantial Galactic H^+ foreground column (*e.g.* Reynolds 1991). If we assume a foreground column of 1.8×10^{20} atoms cm^{-2}, a single temperature fit to the halo spectrum is rejected at the 95% confidence level (top panel). In that case a significant fraction of the halo gas must be cool, about 3×10^5K. Because emission from this gas would be so heavily absorbed, the excess in Fig. 2 would actually imply an order of magnitude larger (in comparison to the several million K gas) X-ray luminosity. If correct, this might be where a large fraction of the supernovae energy needs to go. It would also explain the previous lack of success in detecting hot gas in spirals. Only the very favorable conditions for NGC4631 give us a hint of this

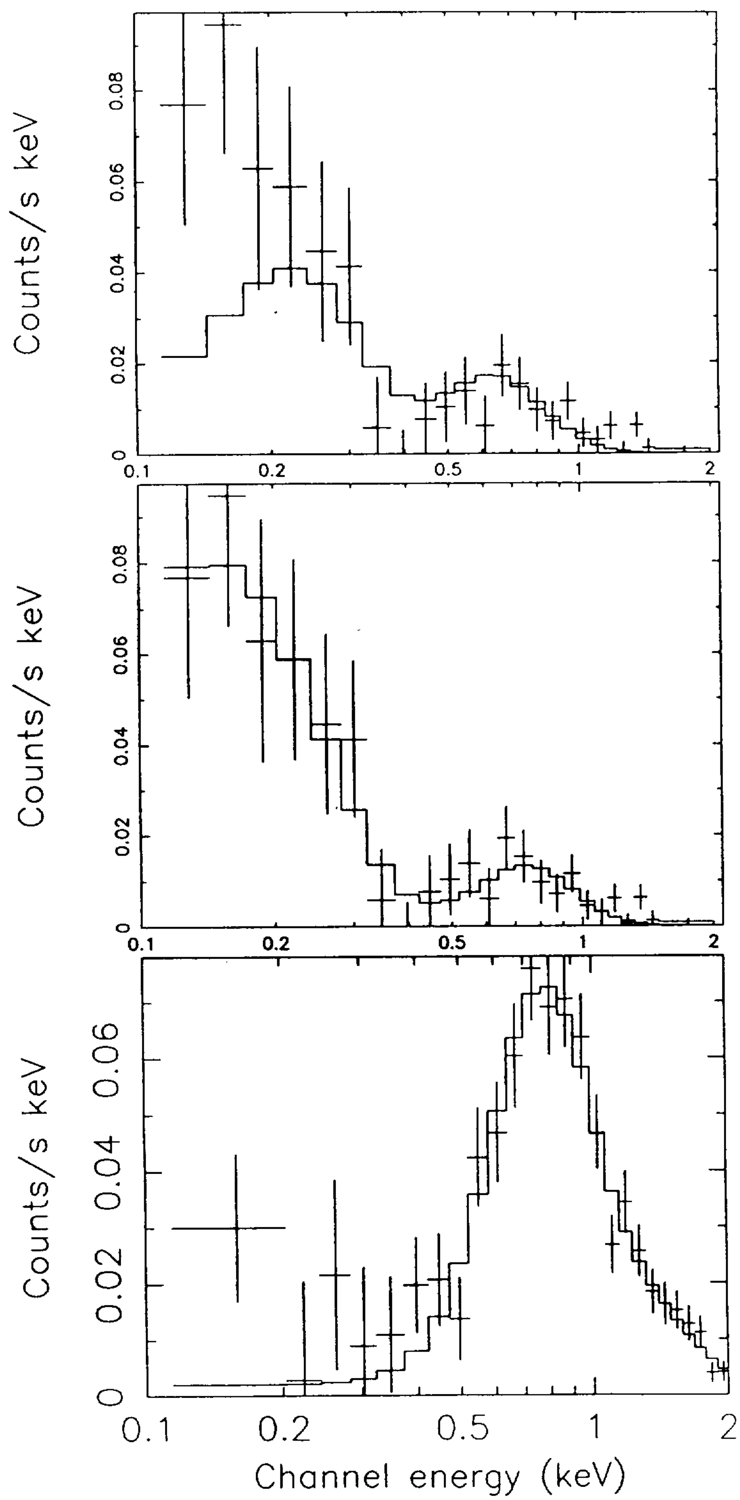

Figure 2. Spectral fits to the halo (top and middle) and disk X-ray data (bottom). The two halo fits correspond to the two options discussed in the text; the halo emission is clearly quite soft. The disk spectrum is harder, partially due to absorption but also to a contribution of hard X-ray sources.

intriguing option and unfortunately it may be hard to find other galaxies where ROSAT data could confirm the presence of large amounts of "cool" hot gas.

A gratifying result is that we have detected X-ray emission from hot gas in both the disk and halo of NGC4631, confirming a long-suspected ISM component, and models of disk-halo interaction (Bregman 1980, Norman & Ikeuchi 1989). On the other hand, the strong tidal interaction does not make NGC4631 a typical spiral, so extrapolation of our results to other galaxies may not be entirely appropriate. Outflows of hot gas have been seen in starburst galaxies (see Bregman and Heckman, these proceedings) and although NGC4631 has not typically been placed in this class, the concentration of halo gas near the central disk might indicate that also here it is especially the central (but not necessarily nuclear) region that is responsible for powering the halo. Thus it remains uncertain how many "normal" spirals will have hot halos. The other likely candidate, NGC891 (Bregman, these proceedings, and Bregman & Pildis 1993) does show a thick disk of hot gas, but not as extensive as NGC4631, possibly because of the larger foreground column which makes it impossible to see a very soft X-ray halo. Apart from these two systems, which both show high star formation rates, even ROSAT may have a hard time detecting extended soft X-ray halos in other "normal" (*i.e.* non-starburst) edge-on spirals, although hot gas in the disks will likely be found.

Acknowledgements

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