ROSAT observations of the dwarf starforming galaxy
Holmberg II (UGC 4305)

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ABSTRACT

We present ROSAT PSPC and HRI observations of the dwarf irregular galaxy Holmberg II (UGC4305). This is one of the most luminous dwarf galaxies ($L_x \sim 10^{40}$ erg s$^{-1}$) detected in the ROSAT All-Sky Survey. The X-ray emission comes from a single unresolved point source, coincident with a large HII region which emits intense radio emission. The source is variable on both year and day timescales, clearly favouring accretion into a compact object rather than a supernova remnant or a superbubble interpretation for the origin of the X-ray emission. However, its X-ray spectrum is well-fit by a Raymond-Smith spectrum with $kT \sim 0.8$ keV, lower than the temperature of X-ray binaries in nearby spiral galaxies.

Key words: galaxies: starburst – galaxies: galaxies-galaxies: individual: UGC 4305, Holmberg II

1 INTRODUCTION

Dwarf starforming galaxies have been extensively studied in X-rays during the last few years. Their X-ray luminosities range from around $10^{38}$ erg s$^{-1}$ (e.g. NGC1569; Della Ceca et al. 1996) up to few times $10^{40}$ erg s$^{-1}$ (e.g. Mrk 33; Stevens & Strickland 1998) more than the whole X-ray luminosity of the Local Group. Many objects appear to be extended in soft X-rays (0.5-2 keV); e.g. NGC1569 (Heckman et al. 1995), NGC4449 (Della Ceca et al. 1997), He 2-10 (Hensler et al. 1997), NGC1705 (Hensler et al. 1998), IC2574 (Walter et al. 1998). This gave support to a ‘superwind’ model for the origin of the X-ray emission. According to this model the numerous supernovae in the starburst drive a galactic scale outflow. Such superwinds are observed in other star-forming galaxies such as M82 (Strickland, Ponn & Stevens 1997) and NGC253 (Fabbiano & Trinchieri 1984). However, in the case of dwarf galaxies where the gravitational potential is low the effects of such superwind can be catastrophic as the hot gas may eventually escape from the galaxy ceasing the star formation. The spectrum of these regions is soft ($kT \sim 0.8$ keV) (e.g Stevens & Strickland 1998) although much softer values have also been reported (e.g NGC1705, Hensler et al. 1997). Even in cases where the emission does not appear to be extended the X-ray emission is usually attributed to a superbubble (e.g NGC5408, Fabian & Ward 1993; Mrk 33, Stevens & Strickland 1998).

In one case so far, (IC 10, Brandt et al. 1997) the X-ray emission, which remains unresolved by the ROSAT HRI, probably originates in an X-ray binary, proving that there are multiple origins for the origin of the X-ray emission in dwarf star-forming galaxies.

In contrast to the situation for the soft X-rays, hard X-ray observations of dwarf star-forming galaxies are scarce. Della Ceca et al. (1996) and Della Ceca, Griffiths & Heckman (1997) observed NGC1569 and NGC4449 respectively with ASCA. Their X-ray spectrum appears to be complex. It can be represented by at least two thermal components: the soft with $kT \sim 0.8$ keV, probably originating from the superwind, while the harder component ($kT \sim 4$ keV) which is spatially unresolved by the ASCA SIS, has an unknown origin. The ASCA observations clearly demonstrate the complexity of the X-ray emission mechanisms in dwarf star-forming galaxies again emphasizing that the origin of the X-ray emission in these objects is still an open question.

1.1 Holmberg II (UGC 4305)

Holmberg II is one of the most luminous dwarf irregular galaxy in the sample of Moran et al. (1996), with an X-ray luminosity of $\sim 10^{40}$ erg s$^{-1}$ in the 0.5-2.0 keV band. The above sample comes from the cross-correlation of the IRAS Point Source catalogue with the the ROSAT All-Sky Survey (RASS). The Moran et al. sample contains mostly AGN but also luminous starburst galaxies. Holmberg II is also one of the most X-ray luminous dwarf starburst for its mass. The ratio of $L_X/M_{\text{gal}}$ is about $4 \times 10^{40}$ erg s$^{-1}$ M$^{-1}$, almost an order of magnitude higher than that of other dwarf starbursts (e.g Stevens & Strickland 1998, Hensler 1997).

Ho observations (Hodge et al. 1994) clearly demon-
strate that there is intense star-forming activity in this galaxy. It is composed of many HII regions (their size ranging from 96 pc up to 525 pc) which appear as bright knots in optical images. The star-formation rate per unit area in Holmberg II is found to be $1.32 \times 10^{-3} M_{\odot} \text{yr}^{-1} \text{kpc}^{-1}$ (Hunter et al. 1998). Most of the HII regions are coincident with 'holes' found in the surface density of atomic hydrogen with VLA observations at 21cm (Puche et al., 1992). This suggests that the HII regions excavate the interstellar medium of the galaxy forming these 'holes'. VLA radio continuum observations (Tongue and Westpfahl 1995) again show that most of the bright HII regions emit intense radio emission. Some regions have typical (non-thermal) supernova remnant spectrum while others display a thermal bremsstrahlung spectrum.

The powerful X-ray luminosity, $L_{X} \sim 10^{38} \text{erg s}^{-1}$, in combination with the proximity of Holmberg II (3.2 Mpc), make it an ideal case for the study of the X-ray emission mechanisms in dwarf star-forming galaxies. In this paper, we report the imaging (section 3), timing (section 4) as well as spectral analysis (section 5) results of Holmberg-II based on four ROSAT PSPC and HRI observations.

2 OBSERVATIONS AND DATA REDUCTION

2.1 The ROSAT PSPC Observations

Holmberg II has been observed on three occasions with the Position Sensitive Proportional Counter (PSPC, Pfefferman et al. 1987) on board ROSAT (Trümper et al. 1984). All the data are now publically available and were retrieved from the LEDAS archive in Leicester. The details of the observations are given in table 1.

For the reduction of the two datasets we have followed the standard procedure, using the ASTERIX package. We excluded data with Master Veto rate higher than 170 counts per second. This gives a net on-source exposure time of 16 ksec in total. Then we extracted a PSPC spectral image cube. In the spectral fits we have excluded all the channels below 10 and above 201 due to the low effective area of the PSPC at these energies as well as to its large uncertainties. In order to obtain the spectrum we have extracted data from a circular region of $\sim 2.0$ arcsec radius. The background was estimated from an annular region between radii of $15''$ and $8.8''$ from the centroid, after exclusion of the discrete sources found with the PSS algorithm (Allen 1992) down to the 4.5$\sigma$ level.

2.2 The ROSAT HRI Observations

Holmberg II has also been observed with the High Resolution Imager (David et al. 1997) on board ROSAT. The FWHM of the Point Spread Function of the XRT+HRI assembly is $\sim 5''$. Again for the reduction of the data we have used the ASTERIX package. In the screening process we have rejected all the data with aspect error greater than 2.

3 SPATIAL ANALYSIS

In order to study the spatial distribution of the X-ray emission, we have extracted PSPC and HRI images with pixel size of 5.0 and 1.5 arcseconds respectively. Figure 1 shows the HRI map overlaid on an O-band PASS image retrieved from the Digitised Sky Survey database located at Leicester. The HRI map was created from the original 1.5'' pixel image after smoothing with a gaussian (3.5'' FWHM). The contours correspond to levels of 0.09, 0.13, 0.18, 0.22, 0.44, 1.11, 2.22, 6.67, 8.0 counts arcsec$^{-2}$. As there are no other X-ray sources in the HRI field, the registration of the X-ray contour on to the POSS image was achieved by assuming that errors in the pointing accuracy and the aspect solution of the HRI are negligible. In reality, there is a scatter of $\sim 6''$ in the difference between the HRI and optical positions of SIMBAD sources, probably originating in residual star-tracker errors (Briel et al. 1997). As a check of the pointing accuracy we have compared the coordinates of the centroids of the point source from the different PSPC and HRI pointings. We found that the coordinates were the same to within $3.8''$ apart from the shortest PSPC exposure where the distance between the centroids was $\sim 10''$.

The most striking result is that the X-ray image shows only one source. Comparing the radial profile of the source with the radial profile of a point source (in this case the star AR-Lac, see figure 2) we see that it is slightly extended. Actually, the source appears elongated in the South-East - North West direction. However, the satellite wobbles in order to smooth the efficiency variations on the microchannel plates (see Briel et al. 1997). The wobble is not always appropriately taken into account in the aspect solution and thus some residual extent is possible. In order to check this possibility, we extracted the HRI image in detector coordinates. It appears that the elongation is along the wobble direction and therefore we conclude that most probably our source is unresolved by the HRI.

In order to search for low surface brightness extended X-ray emission, we have smoothed the PSPC image using a 1.5'' two-dimensional gaussian. The PSPC has the advantage of having a low internal background and thus it can detect large-scale, low surface brightness structures like tenuous hot gas. Again there is just one point source in the field, as confirmed after comparing its radial profile with the radial profile of Mrk 509 which we used as a model point source (Hasinger et al. 1995). The X-ray source is coincident with one of the most luminous HII regions of Holmberg II ($L_{H\alpha} = 3 \times 10^{38} \text{erg s}^{-1}$). Its diameter is 0.5'', which at the galaxy’s distance (3.2 Mpc) corresponds to 352pc (Hodge et al., 1994). Using the $\log N - \log S$ relation in the soft X-ray band (0.5-2.0keV) from Georgantopoulos et al. (1996), we expect 0.07 sources deg$^{-2}$ to be brighter than...
**Figure 1.** Contours from the HRI observation overlaid on a POSS image of the galaxy. The contours correspond to levels of 0.09, 0.13, 0.18, 0.22, 0.44, 1.11, 2.22, 6.67, 8.0 cnts arcsec$^{-2}$. The epoch of the coordinates is J2000.0, and the positional error of the X-ray coordinates with respect to the optical is $\sim 6''$.

**Figure 2.** The HRI radial profile of the off-nuclear source in Holmberg II (crosses) compared with the radial profile of AR-Lac (stars).
The long-term light curve from all the ROSAT observations of Holmberg II. The first point corresponds to the RASS while the last point to the HRI observation. All errors are 1σ. \( \sim 10^{-12}\text{erg s}^{-1}\text{cm}^{-2} \), which is the soft X-ray flux of this galaxy. In the area covered by the HII region we expect to find \( 10^{-5} \) X-ray sources brighter than \( 10^{-12}\text{erg s}^{-1}\text{cm}^{-2} \) by chance, giving us confidence that a confusing foreground or background source is improbable.

4 VARIABILITY

In order to further investigate the nature of the X-ray source, we have constructed a long-term light curve from all five observations of Holmberg II (figure 3). We have used the background subtracted count rates and assumed a power-law model with \( \Gamma = 2.7 \) and absorbing column density \( N_H = 1.2 \times 10^{21}\text{cm}^{-2} \) as found from our spectral fits (see table 2 below). The points are in chronological order; the first point corresponds to the RASS while the last to the HRI detection. All errors plotted correspond to the 1σ level. The errors on the PSPC observations are based on counting statistics only. In contrast, the error on the HRI observation includes the 1σ uncertainty on the absorbing column density (see section below). This is necessary in order to compare PSPC and HRI fluxes as the derived HRI flux is very sensitive on the assumed column density owing to the soft energy response of the HRI. From this figure it is clear that this source is variable by approximately a factor of two.

Next we extracted light curves from the four pointed observations in order to check for short term variability. We have extracted the background subtracted source light-curves using the FTOOLS package. The light curves were created by accumulating photons in 800 seconds bins in order to increase the signal to noise ratio and smooth the effect of wobble. All four light-curves are presented in figure 4. We clearly detect short term variability, but without any obvious periodicity. Using a \( \chi^2 \) test in order to check the non-variability hypothesis we find reduced \( \chi^2 \) of 41.3/11, 74.5/17, 9.4/5 and 35.1/14 for the three PSPC and the one HRI dataset respectively. The null hypothesis probability is then \( 2 \times 10^{-5}, 4 \times 10^{-9}, 0.09 \) and 0.001 for each dataset respectively.

5 SPECTRAL ANALYSIS

For the fitting of the two PSPC spectra we used the XSPEC package, after binning-up the spectra in order to obtain at least 20 counts in each bin. We have fitted the three spectra from the pointed PSPC observations simultaneously (the normalizations were allowed to vary freely between the observations) using various models. The results are presented in table 2. All the single model fits with absorbing column density fixed at the Galactic value, \( 3.42 \times 10^{20}\text{cm}^{-2} \), (Stark et al. 1992) were rejected at above the 99 per cent confidence level. However, a power-law fit with free absorbing column density gave a good fit with a very steep slope \( (\Gamma = 2.68^{+0.17}_{-0.13}) \) and a high column density of \( 12.0^{+1.0}_{-2.0} \times 10^{20}\text{cm}^{-2} \). An even lower reduced \( \chi^2 \) was achieved with a Raymond-Smith thermal plasma with free abundances and absorption. However, when compared to the power-law model, this improvement is statistically significant at less than the 90 per cent confidence level. The best-fit power law model along with the residuals are presented in figure 5. We have also tried double component models of Raymond Smith thermal plasma (R-S) combined with another R-S or a power-law model. These give the same or slightly better reduced \( \chi^2 \) compared to the single component models. The addition of a power-law component to the R-S (free abundance) spectrum is only marginally statistically significant at a level of confidence less than 90 per cent.
These highly luminous X-ray sources are believed to be associated with supernova remnants, superbubbles or X-ray binaries (Fabbiano 1995). Single supernovae in a dense environment can reach high luminosities. Fabian & Terlevich (1996) report the detection of SN1988Z with a luminosity of $L_x \approx 10^{41} \text{ erg s}^{-1}$. Our source is spatially coincident with one of the largest HII regions in Holmberg II, a region which is also a strong source of radio emission (Tongue & Westphal 1995). The spectral index of the radio emission is typical of supernovae remnants. However, the presence of significant long-term (years) and short term variability (days) in X-rays rules out the possibility that the bulk of the X-ray emission comes from diffuse hot gas either in a supernova or in a superbubble. Hence, most probably our source is associated with an accreting compact object.

The X-ray spectrum of this source adds further clues to the origin of the X-ray emission. The spectrum is well-fit either by a single power-law with an absorption ($N_H \sim 1 \times 10^{21} \text{ cm}^{-2}$) well above the Galactic values ($N_H \sim 4 \times 10^{20} \text{ cm}^{-2}$) or a Raymond-Smith spectrum with relatively low temperature ($kT \sim 0.8 \text{ keV}$), very low metallicity and absorption again in excess of the Galactic. The spectrum of the source is much harder than the typical ROSAT spectra of supernova remnants in nearby spiral galaxies, which have temperatures of $\sim 0.36 \text{keV}$ with a dispersion of $0.2 \text{keV}$ (Read et al. 1997). On the other hand, the temperature is softer than that of the luminous sources detected in M51,

| Parameter       | Power-law | Single Temperature | Single Temperature | Power-law | Single Temperature | Single Temperature |
|-----------------|-----------|--------------------|--------------------|-----------|--------------------|--------------------|
| $kT$ (KeV)      | $3.71^{+1.16}_{-0.68}$ | $0.84^{+0.12}_{-0.09}$ | $0.83^{+0.31}_{-0.21}$ | $2.25^{+1.54}_{-0.53}$ |
| $\Gamma$        | $2.68^{+0.17}_{-0.13}$ | $3.36^{+1.25}_{-3.36}$ | $1.1^{+0.1}_{-0.2}$ | $0.59^{+0.1}_{-0.6}$ |
| $Z \times 10^{-3}$ | $1.2^{+0.1}_{-0.2}$ | $0.47^{+0.04}_{-0.03}$ | $0.85^{+0.1}_{-0.03}$ | $1.1^{+0.1}_{-0.2}$ |
| $N_H / \text{cm}^{-2}$ | $1.2^{+0.1}_{-0.2}$ | $0.47^{+0.04}_{-0.03}$ | $0.85^{+0.1}_{-0.03}$ | $1.1^{+0.1}_{-0.2}$ |
| $\chi^2 / \text{d.o.f.}$ | $137.5/129$ | $312.9/129$ | $133.4/128$ | $131.5/127$ |

Table 2. The spectral fitting results of Holmberg II.
kT~1.3-1.7keV (Marston et al. 1995) and of X-ray binary sources detected in other nearby spiral galaxies, kT~1.8keV with a dispersion of 0.13 keV (Read et al. 1997). Interestingly, the spectrum of Holmberg II is very similar to that observed in nearby Wolf-Rayet galaxies (young star-forming galaxies) by Stevens & Strickland (1998). Their X-ray spectra have kT~0.5-1 keV, with luminosities ranging from few times 10^{38} up to 10^{41} erg s^{-1} while the metallicities of the X-ray gas are very low, typically Z = 0.01. Most of these galaxies have the X-ray emission unresolved by the ROSAT PSPC observations. According to Stevens & Strickland (1998) the emission originates in a superbubble. As there are no timing observations of these galaxies, we consider it possible that a large fraction of the X-ray emission, at least in the cases of the compact dwarf galaxies, may originate from the same process as in Holmberg II. As Strickland & Stevens (1997) point out, the ultrasoft components of some black hole candidates have roughly similar spectral characteristics (Inoue 1991) to Wolf-Rayet galaxies and consequently to Holmberg II. The same result is also found for galaxies in the sample of Fourniol et al. (1996), but they cannot distinguish between a binary or a hot gas origin of the X-ray emission in the absence of timing data. Assuming that the putative binary accretes at its Eddington limit, the mass of the central object must be ~200M_{\odot}, well in excess of the mass limit for a black hole formed by the collapse of a normal star. It is difficult to envisage how these high mass off-nuclear black holes formed. However, there are several ways to reduce the required mass. Firstly, accretion at a rate in excess of the Eddington limit: strong magnetic fields may channel the mass onto the accreting object and thus may reduce the mass by a factor of a few. Secondly, the emission may be anisotropic as proposed by Reynolds et al. (1997) for Dwingeloo-X1: one candidate class of objects could be the transient X-ray sources with radio jets displaying superluminal motion (eg GRS1915+105). Finally, the low metallicities derived could result in the increase in the X-ray luminosity of an X-ray binary by as much as an order of magnitude eg. van Paradijs & McClintock (1995).

7 CONCLUSIONS

We have used ROSAT PSPC and HRI observations to investigate the X-ray properties of the nearby (3.2 Mpc) dwarf irregular galaxy Holmberg II. This is one of the most X-ray luminous (unabsorbed L_{x} ~ 3 \times 10^{39} erg s^{-1}) dwarf galaxies in the local Universe. Our main result is that the X-ray emission is unresolved by the HRI with our X-ray source being one of the brightest off-nuclear sources in nearby galaxies. Therefore, the X-ray emission of Holmberg II does not appear similar to other irregular galaxies like NGC1569 and NGC4449, in which the soft X-ray emission has been resolved and is believed to come from large superbubbles of hot gas. Instead the X-ray morphology is more similar to that of the small irregular galaxy IC 10 where the emission comes from a single point source, albeit with much lower luminosity. Our source shows strong variability (by about a factor of two) on both long (year) and short (days) timescales. The variability together with the absence of spatial extent clearly favour a X-ray binary scenario for the origin of the X-ray emission. However, the X-ray spectrum also requires interpretation. The data can be well fit by a thermal spectrum with very low metallicity and a temperature of ~0.8 keV, somewhat lower than the temperature of known X-ray binaries in nearby spiral galaxies. This discrepancy can be alleviated if the emission comes from a black hole candidate which exhibit similar soft spectra, or if the X-ray emission is contaminated by thermal emission from hot gas. Our analysis demonstrates the diversity of the X-ray emission mechanisms in dwarf galaxies. Future high spatial resolution and high energy observations with AXAF and XM/ are necessary in order to unravel the complex X-ray properties of these objects.

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