The ROSAT view of NGC 1365: core emission, the highly variable source NGC 1365–X1, and alignments of surrounding X-ray sources

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Abstract. We present a spectral and spatial analysis of the nuclear and circumnuclear X-ray emission of the prominent southern starburst/Seyfert galaxy NGC 1365. To describe the X-ray spectrum of the core source, we favour a two-component model consisting of about equally strong contributions from a Raymond-Smith plasma (with ∼cosmic abundances) and a powerlaw. The origin of both components is discussed, and a detailed comparison of the X-ray properties with multi-wavelength observations of NGC 1365 and a large sample of type-I AGNs is performed.

Among the surrounding X-ray sources we focus on an analysis of the enigmatic source NGC 1365–X1, which is one of the most luminous and most highly variable off-nuclear X-ray sources known so far.

Positions of further X-ray sources in the field of view are derived and it is briefly pointed out that all HRI sources (except one) are ‘aligned’ relative to the central source.

1. Introduction

NGC 1365 is a prominent southern starburst/Seyfert galaxy. Its nuclear and disk emission-line gas has been investigated in numerous optical studies (e.g., Burbidge & Burbidge 1960, Jörsäter et al. 1984, Schulz et al. 1994, Lindblad et al. 1996, Roy & Walsh 1997). The presence of an AGN was first suggested by Veron et al. (1980) who found broad emission-line Hα indicative of a Seyfert-1.5 galaxy. Surprisingly, just in the nucleus identified by Edmunds & Pagel (1982), Seyfert-typical narrow-line emission line ratios are missing. In the circumnuclear emission-line region, HII region-like line ratios are common indicating widespread circumnuclear star formation.

Summarizing, optical studies suggest that the central region of NGC 1365 consists of an AGN of apparent low luminosity surrounded by a region of enhanced star formation. However, the relationship between the stellar and nonthermal activity and the geometry of the nucleus need further scrutiny.

X-rays are an important probe of the central activity. Here, we present a spectral analysis of ROSAT (Trümper 1983) PSPC and HRI X-ray observations of the core of NGC 1365 and an extraordinary off-nuclear X-ray source which we term NGC 1365–X1 (for details see Komossa & Schulz 1998).

2. The core source

2.1. X-ray spectrum

We studied several spectral models to explain the soft X-ray spectrum. Successful fits can be obtained by either (i) a single Raymond-Smith model (RS) but with strongly depleted abundances of ∼0.1× cosmic, (ii) two component models consisting of a double RS or an RS plus powerlaw (PL), or (iii) a warm ‘absorber’ seen in emission and reflection (‘warm scatterer’).

Since the low inferred abundances of the single RS model are inconsistent with abundance determinations on the basis of optical data (e.g., Alloin et al. 1981, Roy & Walsh 1988, 1997) we favour the two component models. This is in line with recently reported ASCA observations by Iyomoto et al. (1997), who detect a PL component, and particularly, a strong Fe line in the X-ray spectrum of NGC 1365.

We interpret the PL component to arise from the active nucleus, the RS component to be related to the starburst.

2.2. Starburst component

A 100° wide [OIII] enhanced region to the SE of the nucleus was kinematically modelled as an outflow cone by Hjelm & Lindblad (1996). This could be a Seyfert outflow, driven by a wind from the active core, or a starburst outflow, driven by a series of supernova explosions. Assuming that the outflow region evolved from a wind-driven supershell of swept-up ISM we can estimate the starburst contribution to $L_x$ (generated in the shell and the bubble interior to it).
As will be shown below the optically detected AGN could only provide a few percent of the IR emission. Assuming that star formation takes care of the rest we take the IRAS $L_{\text{IR}} = 2.410^{44} \text{ erg/s}$ as an estimate for the bolometric luminosity of the starburst for which models from Gehrz et al. (1983) predict a SN rate between 0.01 and 1 yr$^{-1}$ and $L(\text{H}\alpha)$ in the range $710^{41} - 710^{42} \text{ erg/s}$ of which Kristen et al. (1997) see only $610^{40} \text{ erg/s}$ in the central region. Hence, 90% to 99% of the H$\alpha$ emitters ionized by young stars are hidden. Could this hidden burst supply the X-rays in a wind driven shell?

Using the analytical models of MacLow & McCray (1988) we find that this crude scenario can account for the observed thermal X-ray luminosity if more than 90% of the ionized gas emitting optical lines in the starburst region is obscured.

2.3. AGN component

We now compare the data with the sample of hard X-ray detected AGN from Piccinotti et al. (1982). For this sample, Ward et al. (1988) showed that the luminosities of hard X-rays, H$\alpha$ and mid-IR radiation are well correlated. We represent their results by the relations

\[
\log L_{2-10\text{keV}} = 0.947\log L(\text{H}\alpha) + 3.447 ,
\]
\[
\log L_{2-10\text{keV}} = 1.326\log L(25-60\mu\text{m}) - 15.283 . \quad (1)
\]

For NGC 1365 it turns out that the observed values ($\log L_{2-10\text{keV}} = 41.08$, $\log L(\text{H}\alpha_{\text{broad}}) = 40.82$, $\log L(25-60\mu\text{m}) = 44.87$), do not fit the relations of the Piccinotti sample for which we assume that it defines ‘pure’ AGN properties. E.g., if the hard X-rays come from the AGN in NGC 1365 we would expect $\log L(25-60\mu\text{m}) = 42.5$ which is only 0.4% of the observed 44.87. The remaining IR could either be attributed to star formation or the source for the hard 2-10 keV photons is for a large part obscured which would, however, require column densities exceeding $10^{24} \text{ cm}^{-2}$.

Using the first Piccinotti-sample relation of Eq. 1, the X-rays predict $\log L(\text{H}\alpha) = 39.74$, only 8.3% of the observed 40.82. A possible explanation would be some arrangement of obscuring material in front of the X-ray source or/and the BLR, possibly combined with scattering elsewhere.

Taking H$\alpha$ as representative for the AGN, $\log L_{2-10\text{keV}} = 42.10$, i.e. ten times the observed hard X-ray luminosity would be predicted. This type of solution would fit to our warm scatterer model which could explain both the hard PSPC (and ASCA) PL-like component and the high equivalent width of the FeK complex (like in NGC 6240, see Komossa et al. 1998).

2.4. Place within the unified model

NGC 1365 (with its strong BLR component and weak X-ray emission) does not fulfill expectations of the simplest version of the unified model in which only the torus blocks the light and detection of a BLR would imply an unobscured view of the X-ray source as well. Complicated models appear to be necessary to let this AGN be an intrinsically normal broad-line object.

3. The luminous and highly variable source \textbf{NGC 1365–X1}

The HRI data clearly resolve the nuclear emission from that of the off-nuclear source RX J0333-36 = NGC 1365–X1, and locate the latter on one of the spiral arms (Fig. 3).

The source turns out to be highly variable on the timescale of months. So far, the high-state was reached during the ASCA observation by Iyomoto et al. (1997). We detect a drop in luminosity by a factor of more then ten in the second \textit{ROSAT} HRI observation taken a few months later. The complete X-ray lightcurve is given in Fig. 4.

Intrinsic to NGC 1356, the source is exceptionally luminous, with $L_{2-10\text{keV}} \gtrsim 410^{40} \text{ erg/s}$ in the high-state. Its temporal variability excludes an interpretation in terms of several spatially unresolved weak sources. Although a supernova in dense medium would be an efficient way to reach high X-ray luminosities (e.g., Shull 1980, Vogler et al. 1997), the huge variability on the timescale of months we detect seems to favour an interpretation in terms of accretion onto a compact object.
In Fig. 3 we plot the positions of all HRI sources. Among the nine sources detected in HRI-1, five spatial coincidences are found in HRI-2, the remaining three detected with HRI-2 were below the threshold in HRI-1. In total, twelve sources were detected by the HRI observations. The nuclear source was detected in both observations with comparable count rates. Taking the nucleus as the origin (0,0) of a rectangular coordinate system (we are dealing here with a field of ±0′2 so that we can neglect effects of spherical trigonometry in a good approximation) with the x-axis from west to east (ascending RA) and the y-axis from south to north (ascending declination), eleven extranuclear HRI sources are left.

Sources with nearly the same polar angle φ in this coordinate system are considered ‘to be aligned’. Those ‘on the other side of the nucleus’ have nearly the same polar angle ‘mod 180°’. We found the following ‘alignments’ with the nucleus (i.e. at least two sources are aligned with the nuclear source) or ‘groupings within a few degrees’ (polar angles and the corresponding ‘mod 180°’ are given): Group A1: 12′7 and 191°1 ± 11°1; group A2: 29°6, 207°6 ± 27°6 and 210°2 ± 30°2; group A3: 241°9 and 242°4 and 246°7; group A4: 279°9 ± 99°9 and 102°0; one object with p.a. 171°0 is remaining with no ‘aligned’ counterpart above the threshold of the HRI observations. The maximal observed angular spreads in each group are 1′6, 2′6, 4′8 and 2′1, respectively.

A few tests were commenced to find out whether these alignments suggest a relationship to the nucleus of NGC 1365. To this end, employing a random-number generator we produced eleven positions around the center inside a flat square, with uniformly distributed components x and y. Then the polar angles φ modulo 180° were determined and we looked for groupings among them.

The question arises how to define a situation similar to the observed one. A crude feature of the observations is the occurrence of six angular differences Δφ < 5° (several are significantly smaller!). In a first step, we checked which fraction of the simulations fulfill this criterion. At large numbers (> 1000), we found 1.2% with six Δφ < 5°; in 32% of the cases (the peak of the histogram) there are only three occurrences. We looked at a few particular ‘successes’ and found that none of them reaches the tightness of the observed alignments.

Hence, to interpret the observations by chance alignments requires an extremely rare event. To proceed further in these matters, optical identifications and subsequent spectroscopy, if possible, are necessary and a deliberate search for similar situations around other galaxies would be required. For a study of alignments of bright X-ray sources near galaxies see Arp (e.g., 1997 and references therein) and Burbidge (1998, these proceedings).

### Table 1. Summary of the properties of NGC 1365–X1.

| HRI position (J2000) | α = 3°33′34.5″, δ = −36°9′38″0 |
|----------------------|---------------------------------|
| spectral properties  | Γx ≃ −1.5 for N_Gal, L_x ≃ 2.4 10^{39} erg/s (PSPC low-state) |
| variability          | amplitude factor ≳ 10, within t ≤ 6 months |

4. Further X-ray sources in the field of view

In total, nine and eight X-ray sources with > 3σ are detected within the f.o.v of the first and second HRI observation (dubbed HRI-1 and HRI-2), respectively, and a few additional weak sources with the PSPC. Several sources are variable.

The position of the brightest X-ray source in the f.o.v. is in excellent agreement with that of the BL Lac object MS 03313-36, enabling a rather safe identification. Another source coincides with FCC 129 (see Fig. 3), a low-surface brightness galaxy that may belong to the Fornax cluster. Most other sources are presently unidentified. In particular, none coincides with one of the optical supernovae detected in NGC 1365 (we note that ‘companion 4’ of Turner et al. (1993, their Tab. 2A.B) is within 16-20% of SN1957C; Fig. 3).
5. Summarizing conclusions

We have presented an X-ray analysis of the composite starburst/Seyfert galaxy NGC 1365. Excellent fits of the ROSAT PSPC spectrum are obtained by combining a soft thermal component with a hard powerlaw. The hard component may be either seen directly or can be explained by scattering of the AGN powerlaw at circumnuclear warm high-column-density gas.

A compilation of the multi-wavelength properties of NGC 1365 and comparison with hard X-ray selected AGNs shows that the hard component of NGC 1365 is too faint compared to its broad Balmer line components challenging simple unified models.

According to analytical estimates, supernova driven outflow can fully account for the X-ray luminosity in the Raymond-Smith component if the observed IR emission is mainly provided by the central starburst.

We found that ten of the eleven HRI-detected sources fall into four ‘alignment groups’ which are in polar angle mod 180° (the slope angle of the line connecting the source with the nucleus) each closer together than 5°. Further investigations are required to check whether this is one of the rare possible chance occurrences.

With the ROSAT HRI data, we have precisely located the extraordinary southwest X-ray source NGC 1365–X1 which falls on one of the spiral arms. The source is found to be highly variable (a factor ≳ 10) on the timescale of months. Intrinsic to NGC 1365, its huge luminosity makes it exceptional among stellar X-ray sources. At present, the most likely interpretation seems to be an ultra-powerful X-ray binary.

Acknowledgements. St.K. acknowledges support from the Verbandforschung under grant No. 50 OR 93065. It is a pleasure to thank Per Olof Lindblad for helpful comments and suggestions, and Andreas Vogler for providing the software to plot the overlay contours in Fig. 1. The ROSAT project is supported by the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF/DLR) and the Max-Planck-Society.

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