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Effects of the variability of the nucleus of NGC 1275 on X-ray observations of the surrounding intracluster medium

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ABSTRACT
The active galaxy NGC 1275 lies at the centre of the Perseus cluster of galaxies, which is the X-ray brightest cluster in the Sky. The nucleus shows large variability over the past few decades. We compile a light curve of its X-ray emission covering about 40 years and show that the bright phase around 1980 explains why the inner X-ray bubbles were not seen in the images taken with the Einstein Observatory. The flux had dropped considerably by 1992 when images with the ROSAT HRI led to their discovery. The nucleus is showing a slow X-ray rise since the first Chandra images in 2000. If it brightens back to the pre-1990 level, then X-ray absorption spectroscopy by ASTRO-H can reveal the velocity structure of the shocked gas surrounding the inner bubbles.

Key words: galaxies: active – galaxies: clusters: individual: Perseus – galaxies: individual: NGC 1275.

1 INTRODUCTION
The Perseus cluster of galaxies, the X-ray brightest cluster in the Sky, has an X-ray cool core surrounding the active central galaxy NGC 1275. The jets forming its radio source 3C 84 blow 15 kpc diameter bubbles in the hot gas (Boehringer et al. 1993; Fabian et al. 2000, 2006). Buoyant ghost bubbles lie further from the nucleus, revealing the last 10⁸ yr or more of energy feedback from the AGN to the cool core.

Radio and γ-ray light curves of the active nucleus of NGC 1275 show large amplitude variability over the past 40 years (Abdo et al. 2009; Dutson et al. 2014). The source was bright from the 1960s to about 1990 when it abruptly faded by about an order of magnitude. It was faintest around 2000 and now shows signs of increasing again.

Here, we look at the long-term variability of NGC 1275, finding it to have dropped by about a factor of 20 between when first imaged with the Einstein Observatory in 1980 and Chandra in 2000, rising slowly since then. We demonstrate that the high brightness of the nucleus prevented detection of the inner bubbles with the Einstein Observatory in the (relatively) short exposure times used.

We also examine the possibility of detecting resonance line absorption from the hot gas using the nucleus as a backlight. It appears that if the nucleus remains at the 2006 level or similar then such absorption would be challenging with ASTRO-H, due to its half energy width of 1.5 arcmin causing the nucleus to appear at low contrast against the bright hot gas emission. It will be straightforward for Athena with its angular resolution of 5 arcsec or better. If, however, the nucleus increases to the 1980 level, then it will compromise emission line studies of the central region with ASTRO-H, but make absorption spectroscopy possible. Since our line of sight passes directly through the shocked gas surrounding the 1100 km s⁻¹ expanding southern bubble, such studies would give unique insight and test the growth and energetics of the bubbles.

2 OBSERVATIONS
We investigate the variation in X-ray flux from the central AGN in Perseus by analysing all of the spatially resolved X-ray observations that have been taken of the system, starting with the first Einstein observation from 1979. The observations used are listed in Table 1. In addition we have compiled a comprehensive list of hard energy spectral measurements for NGC 1275 from Copernicus, OSO-7, HEAO-1 A-4, EXOSAT LE, Ginga LAC, OSSE and several balloon experiments (Table 1). Full width at half-maximum (FWHM) for the imaging instruments is tabulated. The early Copernicus estimate contains an uncertain level of cluster emission so is shown as an upper limit.

From the cleaned events files we find the count rate within a circular region centred on the AGN of diameter equal to the FWHM for the instrument used. The count rate was then converted into the 0.5–10.0 keV flux using WebPimms, under the assumption that the spectrum of the AGN is a power law of index 1.65, as was found in the XMM–Newton study of Churazov et al. (2003). Residual cluster
emission is unlikely to contribute significantly to the measured nucleus flux when it is bright.

The resulting X-ray light curve is shown in Fig. 1, with points from different missions labelled and shown with different colours. The X-ray light curve shows a decrease by nearly an order of magnitude from the early 1980s to the 1990s. This is in good agreement with the decrease observed in the 90-GHz radio emission reported in Dutson et al. (2014), which is plotted as the grey points.

3 SIMULATED EINSTEIN IMAGES

The Einstein Observatory’s HRI instrument observed the Perseus cluster for 15.6 ks in 1979 February, and again for 6.6 ks in 1980 February. The central cavities cannot be resolved in either of these images, even when they are stacked together. The cavities remained undiscovered until the first ROSAT HRI observations of Perseus (Bohringer et al. 1993), which showed for the first time clear undiscovered until the first ROSAT HRI observations of Perseus (Bohringer et al. 1993), which showed for the first time clear

Notes. Copernicus: 12, 6, and 2 arcmin apertures; OSO-7: 6.5 deg FWHM; HEAO-1: 1.7 × 20 deg; TESRE balloon: 3 deg; SPARTAN-1: 5 arcmin × 3 deg; SPACELAB-2: 12 arcmin; Ginga: 0.8 × 1.7 deg; OSSE: 3.8 × 11.4 deg.

Table 1. Archival Perseus cluster observations.

| Telescope     | Detector | FWHM (arcsec) | Obs ID            | Year  | Day    | Exposure (ks) | Reference         |
|---------------|----------|---------------|-------------------|-------|--------|---------------|-------------------|
| Copernicus    |          | 120           |                   | 1972 September |        |               | Fabian et al. (1974) |
| UCSD OSO-7    |          |               | h0316n41.xia      | 1972 November 9–27 | 52    | 15.6          | Rothschild et al. (1981) |
| HEAO-1 A4     |          |               | h0316n41.xib      | 1977 August; February, 1978 August | 49    | 6.6           | Primini et al. (1981) |
| Einstein      | HRI      | 3             | ex830724          | 1981 September 29 | 205   | 13.4          | Fabian et al. (1981) |
| TESRE Balloon | LE LX3   | 15            | ex840124          | 1984   | 24     | 2.3           | Fabian et al. (1981) |
| EXOSAT        | LE LX3   |               |                   | 1984 August        |       |               | Matt et al. (1990) |
| SPARTAN-1     |          |               |                   | 1985 September     |       |               | Allen et al. (1992) |
| SPEACLAB-2    |          |               |                   | 1989   | 15–17  |               | Eyles et al. (1991) |
| Ginga         |          |               |                   | 1991 November 28 -12 December 12 | 41    | 10.9          | Boehringer et al. (1993) |
| OSSE          |          |               |                   | 1994   | 217    | 52.9          | Allen et al. (1992) |
| ROSAT         | HRI      | 2             | rh800068a00       | 1996   | 42     | 8.2           | Churazov et al. (2003) |
| ROSAT         | HRI      |               | rh702626a00       | 1997   | 62     | 4.6           |                   |
| ROSAT         | HRI      |               | rh702626a01       | 2000   | 30     | 51.2          |                   |
| XMM           | PN       | 7             | P0085110101PN     | 2001   | 29     | 119           |                   |
| XMM           | PN       |               | P0305780101PN     | 2007   | 340    |               |                   |
| Swift         | XRT      | 7             | sw00036524002xp02 | 2009   | 364    | 4.3           |                   |
| Swift         | XRT      |               | sw00030354003xp03 | 2010   | 219    | 2.1           |                   |
| Swift         | XRT      |               | sw00031770009xp03 | 2013   | 213    | 1.6           |                   |

1 A decrease in X-ray emission at the position of the NW ghost cavity is apparent in the Einstein image, and was commented on at the time (Branduardi-Raymont et al. 1981; Fabian et al. 1981). Since it is devoid of detected radio emission, its true nature was unsuspected.

2 http://hea-www.cfa.harvard.edu/simx/
Finally, in the third row, we show a simulated *Einstein* image of the case where there is no contribution from a central AGN (bottom row), allowing us to demonstrate *Einstein*’s ability to resolve fluctuations in extended X-ray emission from the intracluster medium (ICM) in the idealized case of no point source contamination. We see that even in a 15.6 ks observation, matching the exposure time of the 1979 *Einstein* observation, the inner cavities can just about be resolved. Structure is seen on the scale of the radio source which may at least have triggered further observation. The cavity system is comfortably resolved with an exposure time which is ten times deeper.

4 X-RAY ABSORPTION SPECTROSCOPY USING NGC 1275

In this section, we analyse absorption by the ICM acting on the AGN emission, using a multiphase collisionally-ionized absorber. To calculate the column density of gas in each temperature range, we extracted azimuthally averaged temperature and density profiles from the *Chandra* data, which were deprojected using the DSDEPROJ direct spectral deprojection method (Sanders & Fabian 2007; Russell, Sanders & Fabian 2008). The reduction of the *Chandra* data is described in Sanders & Fabian (2007). We integrated the deprojected density profile along the line of sight to find the column density in the following temperature bands which are tabulated in Table 2: $<2, 2–3, 3–4, 4–5$ and $5–6 \text{ keV}$.

The lowest two temperature components are associated with the high pressure (shocked) rims around the bubbles (Fig. 6). The density jump at the outer edge of the rims is 1.3 and the inferred Mach number is 1.2 (Graham, Fabian & Sanders 2008).

For the absorption, each phase was modelled with a single-temperature *hot* model in SPEX3 (version 2.03.03), which calculates the transmission of a collisionally-ionized equilibrium plasma. For a given temperature and set of abundances, the model calculates the ionization balance and then determines all the ionic column densities by scaling to the prescribed total hydrogen column density. We used five *hot* components with temperatures and hydrogen column densities as quoted in Table 2. We adopted a metallicity of 0.65 (Sanders & Fabian 2007) and a nominal velocity dispersion of 300 km s$^{-1}$ We show the transmission of this multitemperature absorber near the Fe K complex in Fig. 4 with the strongest absorption line labelled. An AGN spectrum provided with both high spatial and spectral resolution would reveal a strong absorption feature at 6.58 keV.

In order to estimate the nuclear emission of NGC 1275, we have analysed the longest on-axis exposure of the Perseus cluster taken with *XMM-Newton*/EPIC in 2006 (ID=0305780101). Data were reduced and corrected for solar flares with the SAS v14 following the standard *XMM–SAS* procedure. We extracted the nuclear spectrum and subtracted the cluster spectrum following the procedure of

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**Figure 1.** Variation in X-ray flux from the central AGN in Perseus from the 1970s to the present day. The grey points show the 90-GHz radio light curve gathered by Dutson et al. (2014), which follows a similar trend to the X-ray light curve.
Churazov et al. (2003). The cluster-subtracted nucleus spectrum was then fitted with a power law and a Gaussian to model the nuclear Fe K emission line, both redshifted and absorbed by the Galactic foreground. EPIC spectra do not have spectral resolution high enough to resolve any narrow absorption lines of the foreground ICM.

The X-ray integral field unit (X-IFU) aboard Athena is planned to have spatial (5 arcsec) and spectral (2.5 eV) resolution at 6 keV high enough to resolve the Fe K lines absorbed by the nucleus. We used the nuclear spectral model fitted with the EPIC spectra as a template model to simulate a 100 ks X-IFU spectrum. On top of the AGN emission the multiphase absorber was tested with three different values of velocity dispersion \( v_\sigma \) (see Fig. 5). The high-quality X-IFU spectrum will easily resolve the lines.

The ASTRO-H Soft X-ray Spectrometer (SXS) with its 5 eV spectral resolution could potentially resolve absorption in the nucleus emission of NGC 1275, but due to the large 1.5 arcmin HEW, the SXS central chip will include both the central AGN and the cluster emission from a region of about 1.5 arcmin width. In order to estimate the cluster emission, we extracted a further EPIC spectrum in an annulus of 0.75 arcmin outer radius and inner radius equal to that of the nuclear region (14 arcsec, see Churazov et al. 2003). We modelled the cluster spectrum with a 4 keV isothermal collisionally-ionized emission model (CIE model in SPEX). The abundances of all the atomic species from carbon to iron were fixed to 0.65 similarly to the multiphase absorber.

We use these EPIC spectral fits to finally define a hybrid model which includes the nuclear emission (power law and Fe K line) intrinsically absorbed by the multiphase ICM plus the unabsorbed 1.5 arcmin cluster emission (CIE), both corrected by redshift and Galactic foreground. We simulate an ASTRO-H/SXS 100 ks exposure for two models with and without AGN intrinsic absorption. We could not distinguish between the models because the cluster accounts for more than 95 per cent of the emission within 1.5 arcmin. A very long exposure above 500 ks could potentially reveal some weak evidence of absorption. However, as previously mentioned, the AGN is brightening in recent years and at some point it may be as bright as in 1980, which was 10 times brighter than in 2006. We have therefore simulated a 500 ks ASTRO-H/SXS spectrum with three models of AGN absorption calculated for a combination of different velocity dispersion and line-of-sight velocity of the multiphase absorber (see Fig. 7). The lowest (blue) line in this figure includes a velocity offset of \(-300\) km s\(^{-1}\) (the bubble is likely rising buoyantly in the cluster potential) with a velocity dispersion of 300 km s\(^{-1}\) as a rough approximation of the expected velocity structure behind the weak shock along our line of sight (Fig. 6). The effects of absorption of the AGN are clearly noticeable.

Resonance line scattering of the emission from the ICM in the cluster is discussed in detail by Zhuravleva et al. (2013) and is not included in our modelling. We note that the largest red and

**Figure 2.** Clockwise from top left: *Einstein* HRI image of NGC 1275; *ROSAT* HRI image of NGC 1275; *Einstein* HRI image of the bright quasar 3C 273 to same angular scale; *Chandra* image of NGC 1275. The *Einstein* image has been lightly smoothed.
Figure 3. Simulated Einstein HRI images with different levels of central AGN X-ray flux and different exposure times (exposure times are $1 \times$, $10 \times$ and $100 \times$ the 1979 Einstein observation exposure of 15.6 ks).

Table 2. Multiphase absorption model.

| $T_{\text{range}}$ (keV) | $T_{\text{adopted}}$ (keV) | $N_{\text{H}}(10^{21} \text{ cm}^{-2})$ |
|---------------------------|--------------------------|----------------------------------|
| <2.0                      | 1.0                      | 2.3                               |
| 2.0–3.0                   | 2.5                      | 5.0                               |
| 3.0–4.0                   | 3.5                      | 4.0                               |
| 4.0–5.0                   | 4.5                      | 2.8                               |
| 5.0–6.0                   | 5.5                      | 1.0                               |

Notes. The model consists of five isothermal ionized absorbers in collisional equilibrium, each of which has fixed temperature $T_{\text{adopted}}$ and hydrogen column density $N_{\text{H}}$.

Figure 4. Transmission of the multiphase absorption model.

Figure 5. Athena X-IFU simulation for the inner 14 arcsec.

blueshifted absorption components seen in the spectrum are likely to be due to the expanding inner bubbles.

We note that the shape of the 6.4-keV neural iron line (shown in Fig. 5) may hold interesting information (Churazov et al. 1998) about the velocity structure of the innermost massive molecular clouds surrounding the nucleus (Salomé et al. 2006; see also Jaffe 1990 for H I absorption against the nucleus).

5 DISCUSSION

We have shown that the X-ray bright nucleus can play both a negative and positive role in the detectability of features in the ICM. When the nucleus of NGC 1275 was very bright back in 1980 it prevented detection of the inner cavities. Our understanding of AGN
feedback in clusters would have begun much earlier had the nucleus been weak at that time. If the nucleus brightens to a similar level in the next decade then it will enable unique absorption spectroscopy of the high pressure expanding rim around the inner southern cavity to be carried out.

Large variability of the jetted nucleus emission is common in cool core clusters. HST-1, part of the inner jet of M87, brightened and faded in X-rays by over an order of magnitude between 2004 and 2008 (Harris et al. 2009). Russell et al. (2013) find significant X-ray variability in the nucleus of A2052 and Hydra-A; Hogan et al. (2015) find high-frequency radio variability in 4 out of 23 central cluster sources. As shown above, an X-ray bright nucleus can enable X-ray absorption spectroscopy. The quasar H1821+643 at the centre of an X-ray luminous cluster at redshift $z = 0.297$ (Fang et al. 2002; Russell et al. 2010; Walker et al. 2014) is a potentially good target.

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