X-ray halos in galaxies

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Abstract. A hot phase of the interstellar medium has now been detected and studied in several objects through its X-ray emission. A proper assessment of its characteristics is relevant for our understanding of several aspects of galaxy properties, from the large scale distribution of matter to the stellar and galaxian evolution, to the dynamics of systems and to the feeding of a central black hole. I will briefly summarize our current understanding of some of the main issues related to the hot gaseous component in galaxies that are fast evolving given the ever more striking and interesting details provided by the X-ray satellites currently operating. I hope to convince you that the X-ray characteristics of the hot gas are quite complex, both in morphology and spectra, in a wide range of objects, which should promote greater efforts in understanding the role played by this component in all galaxies.

Keywords: ISM, galaxies

1. Why is hot gas important?

Because of the implications and relations that a hot phase of the interstellar/intergalactic medium has with several other galaxy-related issues, understanding its properties has become more relevant and intriguing. As just a few examples, gas is closely related to:

• galaxy structure. Gas can be traced at large galactic radii and has been used to study and measure the total gravitational mass in early type galaxies (e.g. Fabricant & Gorenstein 1983)
• evolution of stars, of galaxies and of larger systems. Metal enriched material that is formed in stars gives a measure of stellar evolution; metal gradients indicate how far (how?) metals have traveled from their formation sites; metal concentrations in specific locations could indicate local stripping phenomena
• the dynamics of systems. At high energies different phenomena such as stripping and shocks could be discovered and studied
• active nuclei, who are nourished by gas accretion. When hot, the gas could indeed starve the nucleus rather than feed it, and explain the lack of activity or periodic cycles

The main question is then to find the best candidates to efficiently study the properties of this phase of the InterStellarMedium (ISM).

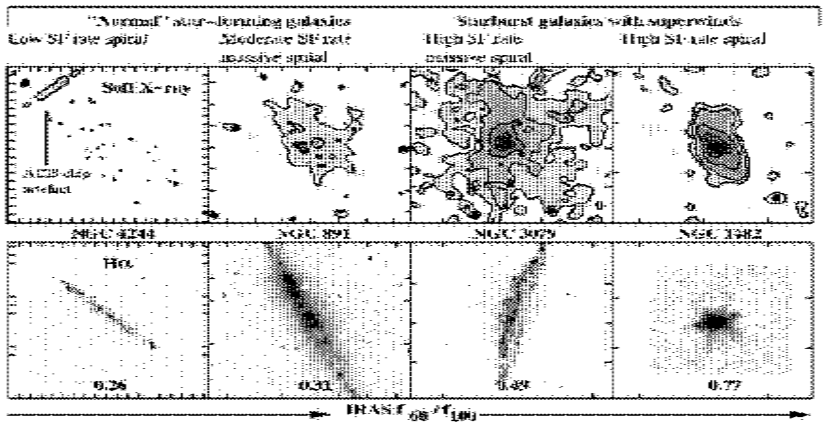


Figure 1. From Strickland et al. (2002b). Top panels: X-ray images in the 0.3-2.0 keV energy band from Chandra data for 4 galaxies from normal to actively forming stars. Lower panels: The same galaxies in the continuum-subtracted Hα+[NII] emission. The arrow at the bottom indicates the increasing IRAS f_{60}/f_{100} ratio, which is used as a measure of the star formation (SF) intensity. The increasingly strong soft X-ray emission associated with increasing SF activity is evident.

2. Where is the hot gas?

There is very little [if any] diffuse emission in normal spiral galaxies. Gas appears to be associated mostly with:

1. **star formation**. A figure from a talk by Strickland et al.2002b provides an excellent example and confirmation of this association. The X-ray images reveal more and more extended soft diffuse emission from hot gas as the line emission and star formation activity become more prominent (see Fig.1).

2. **gravity**. Large quantities of hot gas have been discovered in early type galaxies since *Einstein* observations, and are associated mostly with galaxies at the center of small groups. A long standing issue of whether the large scale gas should be associated with the galaxy or with the group is alive and unresolved as yet, but it is beyond the scope of this talk and it will be mostly [unjustly!] ignored here.

Smaller quantities of gas have recently been found associated with spiral bulges (e.g. M31, NGC 1291) and low luminosity early type galaxies (e.g. NGC 4697), but these are still hard to quantify and characterize. If this is a property of the whole class, a new and interesting field will open up and bring new issues to study and resolve.

It is evident that the characteristics of the gas might not be the same in both cases above, considering the clearly different origins of

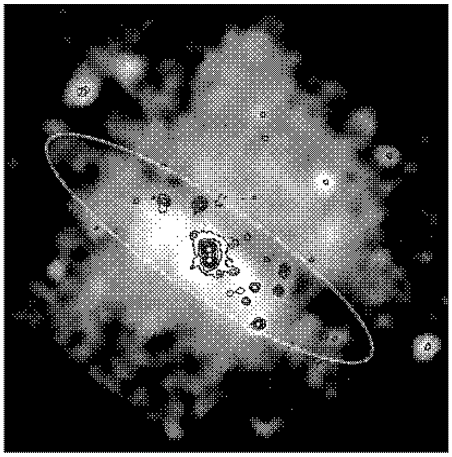


Figure 2.

In this figure, the X-ray halo of NGC 253 in the soft (0.2-0.5 keV) energy band observed with XMM-Newton (courtesy of W. Pietsch) is shown, with the hard emission overlayed as contours. The oval shape indicates the approximate size and orientation of the optical disk. A few point sources are evident in the halo region, otherwise the area above and below the plane appears uniformly filled at these energies.

the two phenomena. It is however likely that different systems will be dominated by only one of the two components, thereby allowing us a relatively clean study of both phenomena separately.

3. Characteristics of the ISM in starburst galaxies/regions

Starburst galaxies are the subject of separate talks in this conference (cf. talks by Dahlem and by Dettmar), so I will briefly review the X-ray evidence, mostly at large scale. The data are fast accumulating but they have not been properly digested yet, and most of the results are still rather qualitative and based on a few examples only.

A large fraction of the total emission of starburst galaxies in the soft X-ray band is due to the hot ISM. The fraction varies in different galaxies, with $> 20\%$ in NGC 3256 (Moran et al. 1999; Lira et al 2002), to $\sim$50% in the Antennae (Fabbiano et al., 2001), to $\sim$80% in M82 (Zezas et al., 2001). Hot gas is found mainly in three regions: (A) the large scale distribution is associated with extraplanar emission, in the galaxy's **halo**, usually associated with evidence of halo emission at other wavelengths (HI, radio continuum, Hα outflows). The emission can be traced to quite large distances: the rather spectacular halo of NGC 253 observed with XMM-Newton in the very soft energy band (Fig. 2) fills a very large region above and below the plane. The halo is usually fueled/fed by a nuclear/galactic outflow/wind. Often "horns" or X-shaped morphologies are observed in galaxies viewed edge-on. A much finer filamentary structure is also observed in halos, e.g. in NGC 3079's halo (Breitschwerdt et al., 2002) with XMM-Newton data

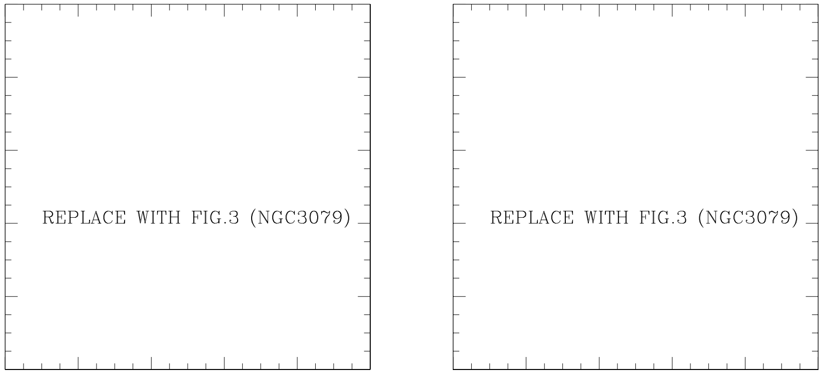


Figure 3. XMM-Newton data of NGC 3079 in the soft band indicate a large scale emission above/below the plane of the galaxy, as defined by the optical image. The filamentary structure of the emission is evident. Filaments are traced out to 13-17 kpc. Three main spurs plus a smaller one are responsible for the X-shaped morphology of the halo. From Breitschwerdt et al. 2002.

and in NGC 253 itself with Chandra data, with spatial fluctuations of ∼130 pc in size (Strickland et al., 2002a). In both cases, these point to a close relation with similar structures in the line emission (cf. above and Fig. 1). (B) The **disk** appears to contain a multi-phase hot ISM. To use the case of NGC 253 again, the data require two temperatures (0.15; 0.5 kT) with no additional absorption and show unquestionable signs of plasma lines, e.g. OVII, FeXVII, that point to emission from a hot ionized medium (Pietsch et al., 2001). It is possible that the multi-temperature of the gas in the disk is to be attributed in part to contamination from emission at higher galactic latitudes projected onto the disk. (C) Possibly the stronger emission is associated with the **nuclear/circumnuclear** regions, from which plumes and outflows are likely to be fueled. These regions appear to be hotter than the rest of the disk (e.g. kT∼6 keV is found in the inner regions of NGC 253 [again!], Pietsch et al.2001), and might contain a higher metal fraction than the outer regions.

A much larger and better studied sample of objects needs to be examined for more quantitative analysis and a broader range of parameters need to be explored before a classification of the X-ray properties of the hot ISM in these galaxies can be finalized.

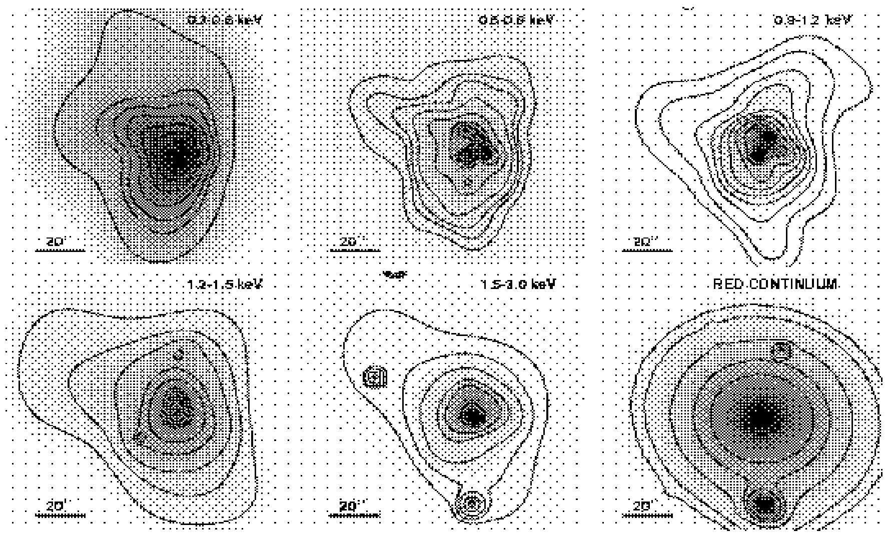


Figure 4. Adaptively smoothed X-ray data of the central region of NGC 5846 at different energies, as indicated in each panel. The red continuum image of the same region (data from the ESO 3.6m + EFOSC) is shown in the bottom right cannel. The comparison between the different images is a clear example of the complexity of the X-ray morphology, and shows how little it reproduces the stellar light distribution.

4. Early type galaxies and groups

The large quantities of gas observed in this class of sources have now been studied in some detail and several general characteristics of the large scale emission are now relatively well established. However, little is known of the emission at intermediate to small scales. New observations have now shown that the gas distribution in the inner regions of early type galaxies can be quite spectacular. At small radii the emission is often disturbed, and arcs-tails-peculiar/unexpected shapes are coupled with inhomogeneous spectral characteristics of the gas. I will concentrate on a few examples from the literature that will illustrate how gas distribution in early type galaxies can be just as interesting as in later types, and rather more unexpected!

4.1. NGC 5846

This galaxy is at the center of a small group, and optically is a rather unperturbed object. The X-ray emission is very extended, roughly azimuthally symmetric and regular, with a large total X-ray luminosity of $L_X(0.2-2\mathrm{keV})$ 7 $\times 10^{41}$ erg s^{-1} within r=10$'$ (Finoguenov et al., 1999). The emission on the sub-arcminute scale instead is much more spectacular and complex: as shown by Fig. 4, an arc structure ("hook"),

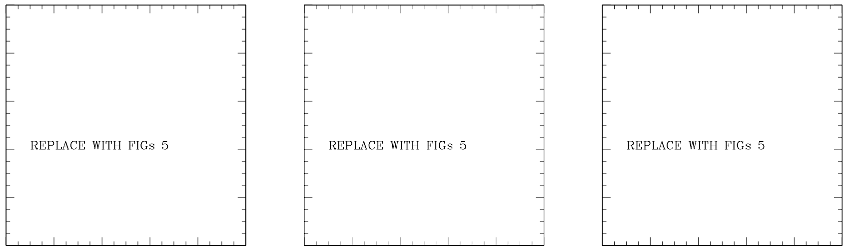


Figure 5. Hα+[NII] image of the inner regions of NGC 5846 (LEFT) on the same scale as the 0.2-2.0 keV emission observed with Chandra (MIDDLE). The Hα+[NII] contours on the X-ray smoothed image (RIGHT) indicate that both morphology and scales are very closely related in this region (from Trinchieri & Goudfrooij [2002]).

a tail pointing S and several knots are evident in the soft energy band, and their relative strengths are clearly energy-dependent.

There is also a curious correspondence with the optical line emission and with the dust distribution, both on scales of $1' - 2'$, as already discovered with the ROSAT HRI (Trinchieri et al., 1997), and on much smaller scales of $2'' - 4''$ (300-600 kpc) discovered with Chandra (Trinchieri & Goudfrooij, 2002). The correspondence is extremely good, but the physical link between the two emissions is still rather puzzling:

– there is no nuclear activity nor a strong Radio Source in the center that would justify/trigger gas excitation
– the origin of the two gas phases are not the same:
  • Hα is most likely of "external" origin, acquired from merging or interaction with smaller, gas rich bodies together with dust. *Here* the internal kinematics supports external origin
  • X rays are "internal", from the ISM of the galaxy presumably accumulated from stellar mass loss.

Why are their morphologies so similar then (Fig 5)? A possible link between Hα [+dust] and X rays is through thermal conduction (Cowie & McKee, 1977; Sparks, Macchetto & Golombek, 1989; de Jong et al., 1990). Cold gas+dust are acquired from the outside at the same time; dust/cold gas act simultaneously on the hot coronal gas, inducing local cooling + excitation into emission; this produces an expected $L_{H\alpha} \sim 1.5 \times 10^{39}\ T_7^{3/2}\ n_{0.01}$ erg s^{-1} (Cowie & McKee, 1977). For the temperature and densities derived from the X-ray observation e.g. in the "hook", of T$\sim 6 \times 10^6$ K and $n \sim 0.35$ cm^{-3} respectively, the Hα luminosity should be $\sim 2.4 \times 10^{40}$ erg s^{-1}, to be compared to a measured $L_{H\alpha} \sim 1.3 \times 10^{40}$ erg s^{-1}. **Too good to be true!**

Can we then assume that this mechanism is responsible for the complex morphologies at small radii seen in other galaxies? The number

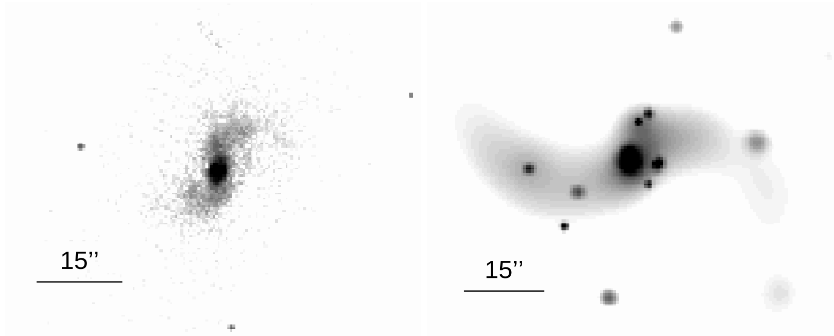
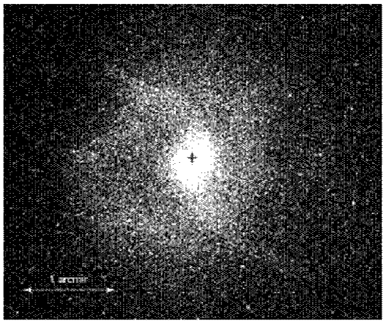


Figure 6. Inner regions on NGC 1553 in Hα+[NII] (left; ESO NTT) and 0.3-1.0 keV band (Chandra archive). In the very soft X-ray band a spiral structure roughly symmetric about a central point-like source is evident, with a possible NS oriented, $10''$ long, inner bar, reminiscent of the Hα+[NII] structure. No such feature is evident in the optical continuum or the X rays above 1 keV.

of cases with both good X-ray and Hα data is limited, but there are a few examples – unfortunately so far NGC 5846 remains the best and perhaps only example for which such close link is observed. For other objects there seem to be a need of other explanations for the small scale morphological perturbation, and unfortunately again each object appears so far to be "unique" (but the cases studies are very few!)

4.2. NGC 1553

The overall emission from NGC 1553 indicates an extended component, slightly elongated NW-SE, consistent with the optical axis (Trinchieri et al., 1997). Even with the lower resolution ROSAT data, several features could be identified that indicated structures at smaller, arcmin size, angular scales. New Chandra data now show that the inner regions are quite complex (Blanton et al., 2001): at energies below 1 keV there is a clear evidence of a spiral structure, a possible inner bar, and a twisted NW-SE elongation at larger radii (cf. Blanton et al. and Fig. 6). At intermediate radii, ROSAT HRI data had already indicated an overall similarity with line emission, although not as close as in the NGC 5846 case (Trinchieri et al., 1997). This similarity appears to break down at small radii (Blanton et al., 2001): there could be a common NS "bar" in the inner $10''$ ((Trinchieri et al., 1997) (Rampazzo et al., 2002), but it is hard to envision thermal conduction to work along the spiral structure where the Hα does not extend. New high resolution Fabry-Perot interferometric data have further shown quite complex gas dynamics in NGC 1553 (Rampazzo et al., 2002), making the possible similarity with the hot phase more difficult to interpret.



Right (from Jones et al. [2002]): Full resolution ACIS-S image of the central regions of NGC 4636 in the 0.5-2.0 keV energy range. A plus sign marks the galaxy center.

Figure 7.

The origin of the spiral feature is better interpreted with adiabatic or shock compression of the ambient gas possibly due to interaction with the radio source (Blanton et al., 2001).

4.3. NGC 4636

A wealth of X-ray data has been accumulated for this X-ray bright galaxy since *Einstein* Observatory times, that indicate a very extended distribution of the X-ray emission, due almost entirely to hot gas at an average temperature of ~ 1 keV and total luminosity of $L_X \sim 2 \times 10^{41}$ erg s^{-1} (Trinchieri et al., 1994; Matsushita et al., 1998; Buote, 2000). From an *Einstein* HRI observation, (Stanger & Warwick, 1986) had already proposed an asymmetric gas distribution at small radii. Chandra data now clearly show symmetric, 8 kpc long, clearly defined spiral-like twisted structures in the inner few arcmin region of this galaxy (Fig. 4.3, (Jones et al., 2002)), coupled with a complex temperature structure of the gas, a weak but measurable temperature gradient (but no cooling flow!) in the inner regions and a number of discrete spectral lines measured with XMM-Newton data (Xu et al., 2002). To date there are no reports of a close morphological relation between the hot and the warm phases, although Hα is detected in this object (Demoulin-Ulrich et al., 1984) with chaotic gas kinematics and with evidence for a kinematically distinct inner region like NGC 5846 (Caon et al., 2000). Jones et al. propose that the X-ray morphology is formed as a result of shocks driven by a nuclear outburst in the recent past. These outbursts would also have implications both in the accumulation of material in the galaxy's center, and in the fueling of a central AGN.

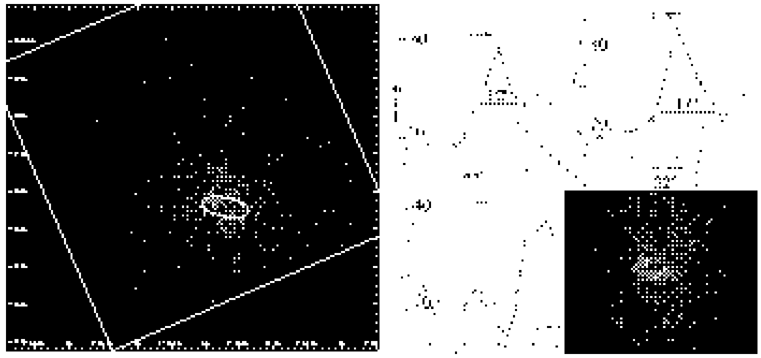


Figure 8. The full Chandra field of IC1262 (LEFT). The oval indicates the optical position of the galxy. A turmoil at the center of the more diffuse emission and a sharp discontinuity in surface brightness are evident even in the raw data, in cuts across the narrow features visible.

5. Unexpected phenomena

Another set of surprises come from the presence of "unsuspected" large scale shocks, not seen/foreseen from the optical data. How many are we missing because we are not looking at the right wavelength?

5.1. IC1262

This galaxy, brightest in a small poor group, became interesting because of its high L_x/L_b ratio as seen in the ROSAT All Sky Survey. X-ray emission was later measured to be very extended (>400 kpc), suggesting a large contribution from the group's potential (Trinchieri & Pietsch, 2000). However, more interesting, the HRI saw an "arc" on $\leq$arcmin scales, that was interpreted as the signature of a shock.

New Chandra data have now shown a quite dramatic view of the system (Fig. 8): a sharp discontinuity east of the central galaxy, with steep drops and a relatively narrow feature along a possible shock front, plus an arc to the NNW, are all indicative of a turmoil in the high energy component, possibly a trace of shocked material caused either by peculiar motions in the system or by a recent merger process. Although a better sampling of the velocity field is needed, neither the optical classification of the galaxy as a cD nor the small velocity dispersion for the group (300 km s^{-1}, (Wegner et al., 1999)) could have suggested anomalous motions of this nature. A proper assessment of the X-ray properties in this and similar systems might be crucial for a more complete understanding of the dynamical and evolutionary properties of small galaxy systems.

6. What can we conclude from all of this?

It is probably too early to draw conclusions from the evidence accumulated so far. However, it is becoming clearer that the small scale gas morphology indicates that the "early- type" galaxy population is far from "quiescent". Same can be said for "cD" galaxies in small/sparse groups. This would indicate that there is ground for more detailed studies of the high energy emission in galaxies; these might reveal unsuspected phenomena like shocks that are crucial for our understanding of the evolution of these systems. The multiwavelength approach is the only one that can provide a complete picture of all the forces at play, and the study of the gaseous components, though complex, has a very high potential for easy discovery of extreme, but perhaps not uncommon, phenomena.

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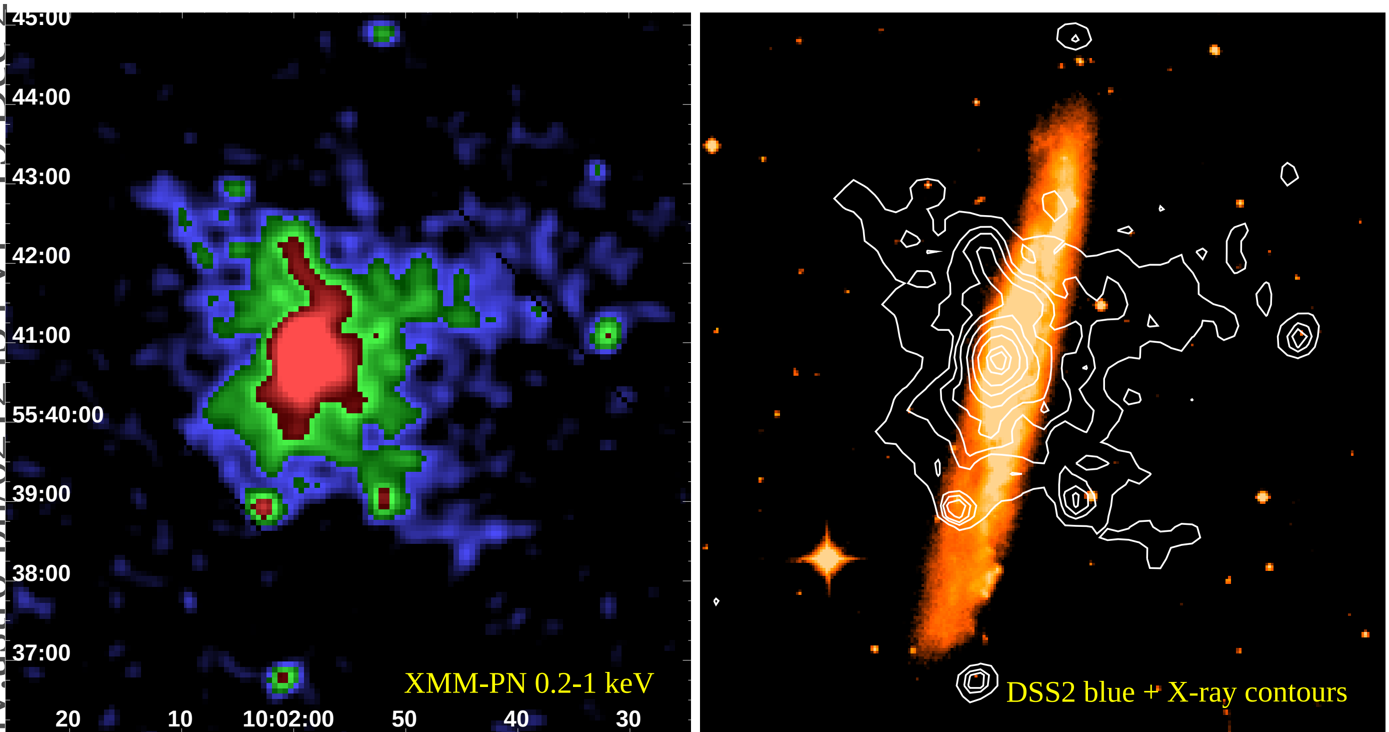
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