X-RAY EMISSION LINES IN ULIRGS

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Abstract. Fits to ASCA data allow the first classification of ULIRG spectra into starburst dominated and AGN dominated. New calculations presented here demonstrate the expected improvement in such analysis, in the near future, when three advanced X-ray missions will enable proper measurements of X-ray lines in such objects.

1. X-ray Observations of ULIRGs

Recent ASCA observations of several Ultra-Luminous IR Galaxies (ULIRGs) enable, for the first time, a careful investigation of the hard X-ray continuum (up to 10 keV) and the emission lines in such sources. The observations (see summary by Nakagawa 1999) are not uniform and represent a fairly inhomogeneous sample of nearby as well as high redshift sources. Therefore, it is premature to make any statistically significant statement about the group properties of ULIRGs. However, some data sets are of sufficiently high quality to investigate the spectroscopic properties and to classify ULIRGs into AGN-dominated or starburst dominated on an object by object basis.

This paper discusses the 0.5–10 keV properties of a sample of 4 ULIRGs, using the best available ASCA data and new theoretical calculations. The emphasis is on the following properties:

- The shape of the 3–10 keV continuum.
- The extended soft X-ray (0.5–3 keV) emission.
- The neutral and highly ionized iron lines near 6.4–8 keV.
- The 0.5–3 keV lines.

Each one of those can be used, in a different way, to distinguish starburst galaxies from obscured AGN and to reveal the relative importance of the two emitting processes.

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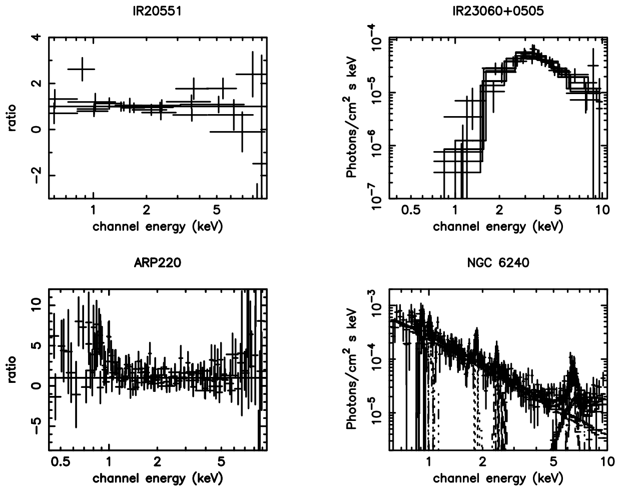

Figure 1. Spectral fits to ASCA observations of four ULIRGs. Left: data/model assuming pure power-law continuua. Note the good fit to the IR20551-4250 spectrum and the poor fit to the Arp 220 spectrum. Right: unfolded spectra. Top: an absorbed power-law. Bottom: absorbed power-law plus emission lines (see Netzer *et al.* 1998 for details).

2. The X-ray signature of AGN

The shape of the 3–10 keV continuum is the cleanest, least ambiguous signature of AGN. Unobscured sources of this type usually show a simple power-law continuum extending well beyond the 3–10 keV band. A good example is IR20551-4250 (Fig. 1). Obscured AGN are more difficult to probe. Complete obscuration (column density of 10^{25} cm^{-2} or larger) is usually associated with a pure reflection spectrum whose shape depends on the ionization level of the reflecting medium. For highly ionized gas, the shape is similar to the original power-law (see Netzer 1996). Partially obscured AGN, like IR23060+0505 and NGC 6240 (Fig. 1) show a combination of pure-reflection spectrum with the original continuum that penetrates through the obscurer at high energies. In either case, the spectrum is very different from the soft spectrum of star-forming regions.

Figure 1 shows power-law fits to the ASCA spectra of 4 ULIRGs. The clear distinction between power-law and thermal continua demonstrate the AGN nature of three of the sources and the starburst nature of Arp 220.

2.1. EXTENDED X-RAY EMISSION

High spatial resolution observations by ROSAT clearly demonstrate that extended 0.2–2 keV emission regions are common in Seyfert 2 galaxies. Such regions can be excited by both powerful SN explosions and stellar winds, in star-forming regions, and by the AGN source (Netzer and Turner 1997 and references therein). Fig. 2 shows theoretical spectra computed for low and high ionization gas excited by a pure AGN source. The two cases are characterized by strong emission lines whose relative intensity depend on the ionization level of the gas. The absolute line intensities are determined by the covering fraction and the optical depth of the extended nuclear gas. Most lines are of extremely large equivalent width because they are measured against a weak reflected continuum. Such lines can originate in regions of several hundred pc in size, similar to the dimension of nuclear star forming regions.

The line ratios in AGN excited regions are vastly different from typical thermal line ratios observed in starburst galaxies. Preliminary analysis of the spectrum of such regions is given in Netzer, Turner and George (1998). Fig. 2 demonstrates what is likely to become the clearest observed signature of AGN type activity in ULIRGs. As shown in the diagram, both neutral (i.e. 6.4 keV) and highly ionized iron lines can be seen. As shown below, typical star forming regions produce very weak, if any, low ionization iron 6.4 keV lines and no He-like and H-like iron lines.

NGC 6240 (Fig. 1) is an ideal bench-mark for future study. Netzer et al. (1998) argued for the AGN characteristics of this source. They have fitted the 0.5–10 keV spectrum by an obscured power-law with several strong AGN-excited lines. Unfortunately, the low-quality ASCA data, and the $\sim 10^{24}$ cm^{-2} obscuring column, prevented from measuring the level of ionization of iron in this source. This can easily be accomplished by Astro-E.

3. The X-ray signature of starburst galaxies

Typical thermal plasma spectra, expected in young star forming regions, are shown in Fig. 3 for two characteristic temperatures of 10^7K and 4×10^7K. There are two major differences between the starburst-type spectra and the AGN excited spectra. First the continuum shape reflects the gas temperature. It is highly unlikely to observe a power-law looking continuum at energies larger than about 3 keV. Second, the emission line spectrum reflects the very different ionization mechanism. Most noticeable is the 6-8 keV region. The typical temperatures are not likely to produce strong iron lines. Furthermore, it is very unlikely to observed *both high and low ionization iron lines* in the same spectrum since this would indicate a temperature range too large to be found in star forming regions. A comparison of the 6-8 keV spectrum in Fig. 3 with the AGN spectrum shown in Fig. 2, demonstrate how a high resolution X-ray spectrum can easily distinguish between the two excitation mechanisms.

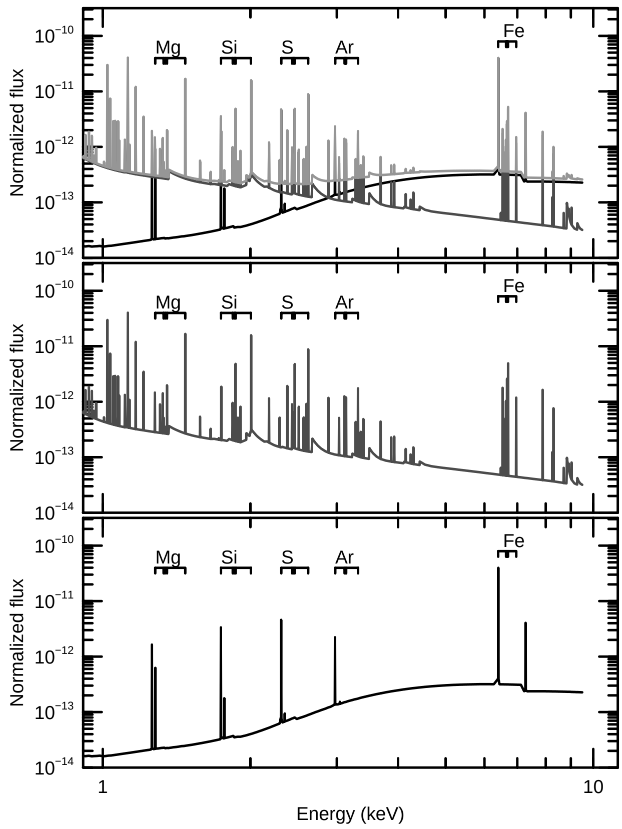

Figure 2. Low ionization (bottom) and high ionization (middle) reflection spectra produced by a central AGN source. A combined spectrum, with a 1:1 flux ratio at 1 keV, is shown at the top.

4. Dust and abundances

Present X-ray observations of starburst galaxies seem to indicate a serious problem in their spectral fitting. Most detailed studies, such as the one by Ptak et al (1997), fit the ASCA spectrum by low metallicity models. In fact, the metallicity deduced in such studies is so low (less than 0.1 solar) that it is in clear contrast with the common wisdom of star forming regions that thought to be of high metal composition. While there is no resolution to this problem, the most likely explanation is that current models of the 0.8–

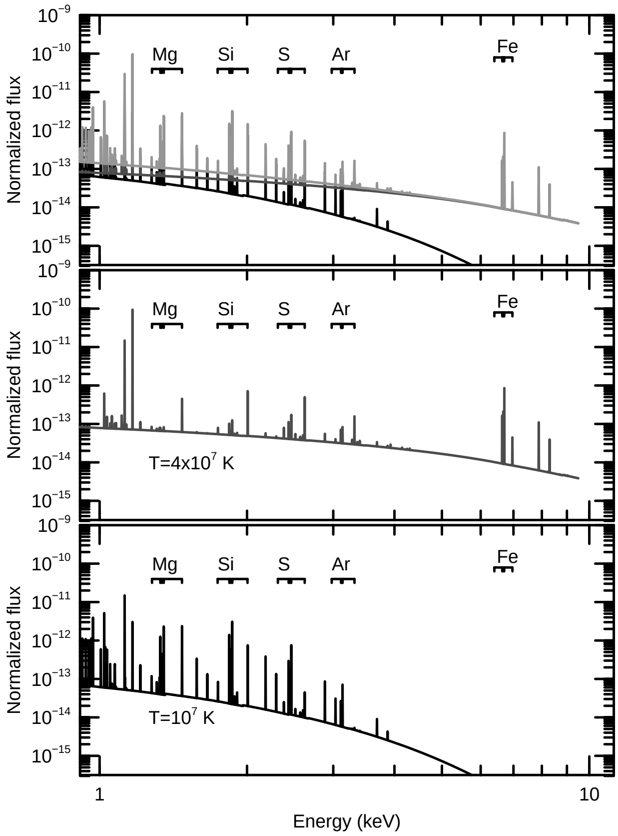

Figure 3. Solar composition thermal plasma spectra with various temperatures, as marked. A combined spectrum, with a 1:1 flux ratio at 1 keV, is shown at the top.

1.3 keV Fe-L line complex is to blame. The strong iron lines in this spectral range, dominate the spectrum and the spectral fitting routines give false impression of the continuum shape. This would imply wrong temperatures and hence wrong composition.

An interesting idea, that ought to be investigated, is that dust is mixed in with the emitting gas. While dust may not survive the hostile environment of the $\sim 10^7$ K gas in star forming regions, this is not the case in AGN type environment. The typical temperature of the photoionized gas is $\sim 10^5$K. If the gas is far away from the central source, and thus not subjected to evaporation by the intense AGN radiation, it may contain enough dust to considerably change its absorption and emission properties. The detailed analysis of the spectrum of dusty ionized gas is beyond the scope of the present paper. We only mention that careful emission line analysis, and investigation of the likely absorption spectrum, can reveal the presence of such dust.

5. ULIRG Study in the AXAF, XMM and Astro-E era

The improved spectral properties of the coming large X-ray missions are likely to settle the AGN-starburst debate about the nature of the dominant energy source in ULIRGs. In particular:

1. AXAF and XMM will provide high resolution spectra ($E/\Delta E \sim 1000$) 0.2–2 keV emission line spectra useful for determining the excitation mechanism.
2. Spectral fits that will avoid the strong Fe-L complex, are likely to solve the apparent abundance anomaly in star forming regions, including those observed in ULIRGs.
3. Astro-E observations will probably detect Fe-K lines in several of the most luminous ULIRGs. The relative ratio of the high and low ionization iron lines will provide a very clear signature of the main excitation mechanism.

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