THE X–RAY SPECTRUM OF COMPTON–THICK SEYFERT 2 GALAXIES

GIORGIO MATT

Dipartimento di Fisica, Università degli Studi "Roma Tre", Via della Vasca Navale 84, I–00146 Roma, Italy

ABSTRACT. Current ideas on the X–ray spectrum of Compton–thick Seyfert 2 galaxies are reviewed, and a brief description of the four presently known sources of this class are given.

1. Introduction

In the unified model for Seyfert galaxies (Antonucci 1993 and references therein), type 2 sources are believed to be intrinsically identical to type 1's, but observed at inclination angles, with respect to the symmetry axis of the molecular torus (see e.g. Ward 1994), greater than the torus half–opening angle. Therefore, at least in optical/UV, the nucleus of Seyfert 2 galaxies is not directly visible.

In X–rays the situation is more complex. In this band, the two most important interactions between photons and (cold) matter are photoabsorption and Compton scattering. The photoabsorption cross section strongly depends on energy (decreasing approximately as $E^{-3.5}$), while the Compton cross section is constant, at least up to the Klein–Nishina decline. The two cross sections, for solar chemical composition, are equal at about 10 keV. If the column density of the torus is smaller than $\sigma_T^{-1} \sim 1.5 \times 10^{24}$ cm[−]² , the nucleus turns out to be visible above a few keV, and the sources are named Compton–thin, because the matter is optically thin to Compton scattering. If, on the contrary, the column density exceeds that value, the matter is optically thick to Compton scattering; for Compton optical depths of ∼a few, the nucleus becomes practically invisible also in hard X–rays because, after a few scatterings, photons are redshifted down to the photoabsorption dominated regime. These sources are called Compton– thick Seyfert 2 galaxies, and can be observed in X–rays only in scattered light, as will be discussed in the next section. Of course, they are very faint in X–rays and only a handful (four, excluding the borderline source NGC 4945) of them are presently known.

2. The X–ray spectrum of Compton–thick sources

Even if the type-1 nucleus is, in Compton–thick sources, completely obscured in the whole X–ray band, its existence is revealed by scattered light. Two scattering media are thought to be present in the vicinity of the nucleus: (a) the optically thin matter

responsible for the scattering and polarization of the optical broad lines in several Seyfert 2 's (the so-called "warm mirror"), and (b) the inner surface of the torus itself which, in these sources, is optically thick by definition.

(a) Scattering from the warm mirror of the nuclear continuum radiation produces a spectrum which is practically identical to the nuclear spectrum up to energies at which Compton recoil is important, where a cut–off occurs (Matt 1996; Poutanen et al. 1996). Therefore, its shape is expected to be, at least below say a few tens of keV, a power law with photon index ∼2 (Nandra & Pounds 1994). Line emission from ionized atoms is also expected, iron $K\alpha$ lines being among the most prominent (other lines, e.g. from carbon, oxygen and neon, can also be very intense; however, they are often diluted by other continua arising in soft X–rays, e.g. from starburst regions. Fe xxv (6.7 keV) and Fe xxvi (6.97 keV) K α line emission from such a medium is discussed in detail by Matt, Brandt & Fabian (1996). Their equivalent width with respect to the continuum reflected from the warm mirror itself can be as high as a few keV.

(b) As shown by Ghisellini, Haardt & Matt (1994) and Krolik, Madau & Zycki (1994), the spectrum of the nuclear radiation scattered from the inner surface of the torus is similar to that observed in many Seyfert 1 galaxies (Mushotzky, Done & Pounds 1993 and references therein), where the reflecting matter is believed to be the inner accretion disc. It is usually referred to as the Compton reflection component. It is very flat in the classical 2–10 keV band (photon index less than 1) due to the increasing ratio of Compton scattering to photoabsorption cross sections (e.g. Lightman & White 1988). A fluorescent $K\alpha$ line at 6.4 keV from neutral iron, with an equivalent width with respect to the continuum reflected by the same matter of about $1-2 \text{ keV}$ (e.g. Matt et al. 1991; Ghisellini, Haardt & Matt 1994; Reynolds et al. 1994) is also expected, as well as fainter lines from lighter elements (Reynolds et al. 1994; Matt, Fabian & Reynolds 1996).

The intensity of the radiation from the warm mirror depends mainly on the optical depth of the mirror itself, while that of the torus component depends basically on the inclination angle of the system (see Matt, Brandt & Fabian 1996). Their relative ratio can therefore be very different from source to source. Three cases are then possible:

 $i)$ The warm mirror component dominates over the torus component. A $2-10$ keV spectrum composed by a power law with photon index about 2 plus strong ionized lines is expected. No sources of this kind have been discovered yet to our knowledge.

ii) The two components are of the same order. A spectrum with an intermediate or flat photon index (1–1.5 or less) and both neutral and ionized lines is expected, and it has indeed been observed in NGC 1068 (Ueno et al. 1994; see below for a revised analysis) and NGC 6240 (Iwasawa, private communication). It is worth stressing that it is possible to observe in one and the same source a continuum dominated, above a few keV, by the torus component and also a complex iron line, as the lines from ionized matter can be very bright and then visible even if the relative continuum is much smaller than the torus one (this actually seems to be the case for the two sources of this group).

iii) The torus component dominates over the warm mirror component. A very flat (less than one) spectrum with a strong 6.4 keV iron line is expected, and actually observed in NGC 6552 (Fukazawa et al. 1994) and in the Circinus Galaxy (Matt et al. 1996).

In the next section we will briefly discuss each of the four currently known Compton– thick sources.

3. Group II sources

NGC 1068 is surely the best studied among Compton–thick Seyfert 2's (and maybe among all Seyfert 2's). Its X–ray spectrum is composed by thermal–like emission, probably due to a starburst region (Wilson et al. 1994) and dominating below 3–4 keV, and a hard power law with superposed a complex iron line, composed by a neutral component at 6.4 keV and contributions from He– and H–like iron (Ueno et al. 1994 and references therein). Iwasawa, Fabian & Matt (1996) have recently re–analysed the ASCA PV observation and found that: a) the photon power law index is smaller than previously estimated, being less than 0.4. This value is consistent with a pure reflection continuum. b) A feature just redwards of the neutral iron line is present, with a flux of about 10 percent of that of the line, and interpreted as the line Compton shoulder, i.e. line photons scattered once before escaping from the matter. This feature is predicted by the reflection models (see e.g. Matt, Perola & Piro 1991) but never detected so far. c) The ionized iron lines are both redshifted; the derived velocity of the emitting matter is about 4000–5000 km/s.

The interpretation of the spectrum above a few keV is that we are looking at reflection from both the warm mirror and the obscuring torus, with the former component smaller but not completely overwhelmed by the latter one, so that the continuum is dominated by the torus reflection but the lines from the ionized matter (possibly forming a wind, as suggested by its relatively high velocity) are still visible.

NGC 6240 is one of the most famous merging system and a prototype ultraluminous infrared galaxy. In X–rays, the source has been observed by both ROSAT–PSPC (Fricke & Papaderos 1996) and ASCA (K. Iwasawa, private communication). The ROSAT– PSPC revealed extended soft X–ray emission, which can be explained by a starburst model. The ASCA spectrum is complex, consisting of: a thermal–like component, consistent with the ROSAT observation and dominating in soft X–rays; a quite hard power law; both neutral and ionized iron lines. The hard spectrum is very similar to that of NGC 1068, and can be explained in the same way.

4. Group III sources

NGC 6552 was serendipitously observed by ASCA (mainly thanks to the very prominent 6.4 keV iron line; Fukuzawa et al. 1994), and then identified with a Seyfert 2 galaxy. Its X–ray spectrum is well described by a pure Compton reflection continuum (Reynolds et al. 1994), and then interpreted as reflection from cold matter (possibly the torus) of an otherwise invisible X–ray nucleus. A heavily absorbed power law maybe also be present, but the source is too faint to permit any strong conclusion on this and other spectral details.

The Circinus Galaxy is a nearby (4 Mpc) Seyfert 2 with a very prominent ionization cone, strong coronal lines and water maser emission (see Oliva et al. 1994 and references therein). Before ASCA, it was never observed in X–rays, apart from a detection in the ROSAT all sky survey. The ASCA spectrum is quite remarkable, showing a very prominent iron K α line at 6.4 keV, many other lines from lighter elements as well as the K β iron line, and a very hard continuum (Matt et al. 1996). Below about 2 keV,

a further component emerges, possibly due to a starburst region. Above that energy, the spectrum is well described by a pure reflection component. Lines from elements lighter than iron are also expected in this model (Reynolds et al. 1994; Matt, Fabian & Reynolds 1996). However, their observed intensities and centroid energy are not entirely consistent with reflection by cold matter; improved ASCA–SIS calibration matrices have to be waited for before further addressing this issue.

5. Conclusions

The model described in Sec.2 for the X–ray spectrum of Compton–thick Seyfert 2 galaxies is fully consistent with the observations of the four known sources of this class. A prediction of this model is a spectral cut–off at a few tens of keV due to Compton recoil. BeppoSAX and RXTE observations will then be valuable in testing the model.

Acknowledgements

I thank all the colleagues who collaborate with me on this topic. I'm particularly indebted to K. Iwasawa for allowing me to quote his results on NGC 6240 before publication.

References

Antonucci, R.R.J., 1993: Ann. Rev. Astron. Astrophys. 31, 473.

Fricke K.J., Papaderos P.: 1996, Proc. of the conference "Roentgenstrahlung from the Universe". MPE Report n.263, p.377.

Fukazawa Y., et al.: 1994, Publ. Astron. Soc. Japan 46, L141.

- Ghisellini G., Haardt F., Matt G.: 1994, Mon. Not. R. Astr. Soc. 267, 743.
- Krolik J.H., Madau P., Zycki P.T.: 1994 *Astrophys. J.* 420, L57.
- Iwasawa K., Fabian A.C., Matt G: 1996, Mon. Not. R. Astr. Soc., submitted.
- Lightman, A.P., White, T.R.: 1988, Astrophys. J. 335, 57.
- Matt, G.: 1996, Proc. of the conference "Roentgenstrahlung from the Universe". MPE Report n.263, p.479.
- Matt G., Brandt W.N., Fabian A.C.: 1996, Mon. Not. R. Astr. Soc. 280, 823.
- Matt G., Fabian A.C., Reynolds C.S: 1996, Mon. Not. R. Astr. Soc., submitted.
- Matt G., Perola G.C., Piro L.: 1991, Astron. Astrophys. 245, 25.
- Matt, G., et al.: 1996, Mon. Not. R. Astr. Soc. 281, L69.
- Mushotzky R.F., Done C., Pounds K.A.: 1993, Ann. Rev. Astron. Astrophys. 31, 717. Nandra, K., Pounds, K.A.: 1994, Mon. Not. R. Astr. Soc. 268, 405.
- Oliva E., Salvati M., Moorwood A.F.M., Marconi A., 1994: Astron. Astrophys. 288, 457.
- Poutanen J., Sikora M., Begelamn M.C., Magdziarz P: 1996, Astrophys. J. 465, L107.
- Reynolds C.S., Fabian A.C., Makishima K., Fukazawa Y., Tamura T.: 1994, Mon. Not. R. Astr. Soc. 268, L55.
- Ueno S., Mushotzky R.F., Koyama K., Iwasawa K., Awaki H., Hayashi I.: 1994, Publ. Astron. Soc. Japan 46, L71.

Ward M.J, ed.: 1994, Proceedings of the Workshop on "Evidence for the Torus", Oxford. Wilson A.S., Elvis M., Lawrence A., Bland–Hawthorn J.: 1992, Astrophys. J. 391, L75.