X-RAYS FROM ACTIVE GALACTIC NUCLEI

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Recent X-ray observations of active galactic nuclei and Seyfert galaxies in particular are briefly reviewed. The application of the efficiency limit to rapidly varying luminous sources such as NGC 6814 is discussed. It is argued that the variability and probable MeV spectral turnover imply that most of the electrons which radiate the observed flux are only mildly relativistic. A possible link between the steep soft X-ray spectra and featureless optical continua of BL Lac objects is considered.

1. INTRODUCTION

Most of the electromagnetic energy radiated by active galactic nuclei is at X-ray wavelengths. The X-radiation is therefore likely to be of great importance in understanding the dominant energy release processes that operate there. This, together with the good all-sky coverage that has been obtained with single instruments and the wide range of timescales that have been sampled, make the interpretation of X-ray observations of active galactic nuclei a worthwhile task.

I shall concentrate here on results obtained from well-studied Seyfert galaxies and largely ignore the growing body of X-ray data on quasars (Tananbaum et al., 1979; Ku, Helfand and Lucy, 1980; Zamorani et al., 1981; and others). These data at present reveal more about the statistical properties of a large number of objects in the relatively narrow (0.5 - 3 kev) band than about the emission process itself. Some consequences of the variability and MeV turnover are discussed in terms of the source efficiency and radiative processes in Sections 3 and 4. The influence of X-radiation on the surrounding gas is considered in Section 5. These sections closely follow my interests. Other recent theoretical discussions of X-ray emission in active galaxies may be found in Lightman (1981) and in Cavaliere (1981, 1983).

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 491–498.

2. X-RAY OBSERVATIONS OF SEYFERT GALAXIES

Einstein, Ariel-5, HEAO-1 and balloon-borne observations have combined to give a picture of the spectrum and variability of Seyfert galaxies from ∿ 0.2 keV to 2 MeV. A power-law spectrum with some in-source photoelectric absorption in low-luminosity sources and a turnover above 200 keV (and probably around 1 MeV) fits most of the observations. Variability on timescales exceeding a day is common; more rapid changes are the exception.

Recently, HEAO-1 A2 and A4 observation of Seyfert galaxies have been combined to show that the mean power-law energy index is 0.62±0.04 from 2 to 165 keV (Rothschild et al., 1982). No spectral break is required, although increasingly sharp changes could be fitted above ∿ 50 keV. Significant columns of absorbing material, N_H, appear to be present in both narrow-line and broad-line galaxies with $N_H \gtrsim 10^{22} cm^{-2}$ for X-ray luminosities $L_X \lesssim 10^{43} erg\ s^{-1}$ (Mushotzky, 1982; Maccacaro, Perola & Elvis, 1982; Fabian, Kembhavi & Ward, 1981). At much higher energies, balloon-borne observations of NGC 4151 and a few other active galaxies (Schönfelder, 1982; Perotti et al., 1981) suggest that a flat spectrum continues to about an MeV, beyond which it steepens (as it must in order to be consistent with the SAS II upper limits at ∿ 100 MeV). The X-ray luminosity function of active galaxies (Piccinotti et al., 1982) can be used to predict their contribution to the X-ray background. This contribution increases from ∿ 20 percent around 5 keV to possibly all the flux above ∿ 200 keV. The 'MeV bump' in the background spectrum is then entirely due to active galaxies and the steepening above ∿ 2 MeV must be reflected in the spectra of individual sources. More, and better quality, spectra in the range 100 keV to 10 MeV are needed before we can safely conclude that the spectral break does occur at ∿ 1 MeV, although this seems likely on the basis of present data. It is interesting to note that no evolution of the X-ray luminosity function is required in this explanation of the 'MeV bump'.

Significant intensity variations are seen in most active galaxies on timescales exceeding ∿ 1 day (Marshall, Warwick & Pounds, 1981; Mushotzky, 1982; Maccacaro, Perola & Elvis, 1982; Tananbaum, 1980). Faster variations have been well observed in NGC 6814 (Tennant et al., 1981) and reported from NGC 4051 (Marshall et al., 1981), NGC 4151 (Tananbaum et al., 1979) and 1525+227 (Matilsky, Shrader & Tananbaum, 1982). Tennant and Mushotzky (1982) find that most active galaxies do not vary on timescales ranging from minutes to a few hours by more than 10 percent. The X-ray light curve of NGC 6814 (Tennant et al., 1982) shows large amplitude (∿ 100 percent) changes in hundreds of seconds with no particular timescale appearing dominant. The X-ray spectral slope appears to remain fairly constant throughout the intensity variations in active galaxies, although some of the changes in NGC 4151 are actually due to the absorbing column (Barr et al., 1977). There is some evidence for large spectral variations in BL Lac objects (Worrall et al., 1981).

3. THE IMPLICATIONS OF VARIABILITY

The lack of rapid variability on timescales shorter than a day in most active galaxies suggests that a light day, or 3.10^{15} cm, is a characteristic scale for the emission region. This corresponds to about 10 Schwarzschild radii, r_s, for a 10^9 $M_\odot$ object; which is where most of the energy would be released from such a massive accreting black hole. Limiting the total luminosity to less than the Eddington limit suggests that the central masses exceed 10^7 - 10^9 $M_\odot$ for the more luminous nuclei. Application of these arguments to the 100s variability of NGC 6814 leads to a mass of only 10^6 $M_\odot$, although it should be noted that we might here be viewing a few small blobs orbiting a large central mass rather than a more uniform spherical (and concentric) emission region.

In most situations, the outgoing radiation interacts with the matter responsible for the radiation. This leads to the "efficiency limit" (Fabian, 1979; Fabian & Rees, 1979), which is a generalisation of the fireball consideration of Cavallo & Rees (1978). A change in luminosity, ΔL, on a timescale Δt implies a mass M of radiating matter given by

$$\Delta L.\Delta t = \eta Mc^2$$

where η is the matter to energy conversion efficiency. If the matter is in a sphere of radius R and the photon-matter scattering cross section σ gives a total optical depth τ then $M \simeq 4R^2\tau m_p\sigma^{-1}$. Δt is minimized for a given mass if $\tau = 1$; a more compact sphere leads to increased Δt via photon diffusion and a more diffuse one leads to larger light crossing times. R is then approximately equal to $\frac{1}{2}c\Delta t$ and we obtain

$$\Delta L \lesssim \frac{\eta c^4 m_p \Delta t}{\sigma}$$

which for the Thomson cross-section and an efficiency $0.1\eta_{0.1}$ is

$$\Delta L \lesssim 2.10^{41}\ \eta_{0.1}\Delta t \text{ erg s}^{-1}.$$

Substantial luminosity variations are unlikely to occur on timescales shorter than given by this limit, which appears to be fairly well obeyed by most sources in the Universe, despite its simplicity. The only event seriously over the limit (by several orders of magnitude) is the 5 March 1979 γ-ray burst, if it was at the distance of the LMC. A thin shell geometry (with necessary strong anchoring magnetic field) can however explain this discrepancy (Guilbert, 1982). The X-ray variation in NGC 6814 and 1525+227, together with some possible optical changes in BL Lac objects lie close to, or just above the limit.

P. Guilbert (1982) has pointed out that even mild relativistic effects in source motion ($v = \beta c$) can be very important in relaxing the efficiency limit. This is because a boost-factor of $\gamma^5(1+\beta)^5$ is introduced (2 factors from aberration, one from blueshift and 2 from time factors) which exceeds 5 for $\beta > 0.5$. Thus random motions of blobs at $\sim 10\ r_s$ can lead to large variations with reasonable probabilities. Narrow-band observations of a steeply-falling spectrum can lead to further amplification via the Compton-Getting effect.

The application of the efficiency limit assumes that the electrons, which radiate most of the energy, can obtain that energy from the protons which carry most of the energy, on a timescale shorter than the photon escape time, i.e. $t_{e-p} \lesssim \Delta t$. If two-body processes determine t_{e-p} then the Spitzer (1956) formula is appropriate;

$$t_{e-p} = 115\ (\theta_e + \theta_p)^{3/2}\ \frac{R}{c\tau}\ \text{s},$$

where θ is the electron (proton) temperature in units of its rest mass. At the limit, $\Delta t \approx 2r/c$, so that $(\theta_e + \theta_p) > 0.067$, or in general

$$kT_e \lesssim 35\ \text{keV}$$

(Guilbert, Fabian & Stepney, 1982). Rapid variability and spectra extending to several hundred keV imply that the efficiency is high, that relativistic processes operate or that some faster process than two-body relaxation is operating. If this last option turns out to be true and some plasma process dominates, then we have neither a way of estimating the coupling timescale nor any idea of the shape of the electron velocity distribution (Gould, 1982).

We see that fairly model-independent constraints can lead to information on the source efficiency, motions and energy flow. NGC 6814 is a good test case as its spectrum extends with a slope of ~ 0.7 to at 100 keV (Rothschild et al., 1982). If the 100s variability occurs simultaneously up to an energy of 100 ε keV, then the source efficiency $\eta \gtrsim 0.1\ \varepsilon^{0.6}$ ($H_0 = 50$ km s^{-1} Mpc^{-1}).

The observational evidence presented in Section 2 suggests that the spectrum does extend up to $\varepsilon \sim 10$. This probably means that both a plasma electron-proton coupling process and mildly relativistic motions are required.

4. RADIATION PROCESSES

Various possible routes for producing X- and γ-rays are shown in Figure 1. Those paths with the shortest timescales will lead to most of the emission. Compton processes generally dominate over bremsstrahlung in compact sources (Lightman, Giacconi & Tananbaum, 1978). These can produce power-law spectra (often called "non-thermal" spectra) even from thermal electrons (Katz, 1976) and so spectral shape is not a good determinant of the ratio of energy in thermal gas compared with relativistic gas (i.e. cosmic rays). The MeV turnover and rapid variability

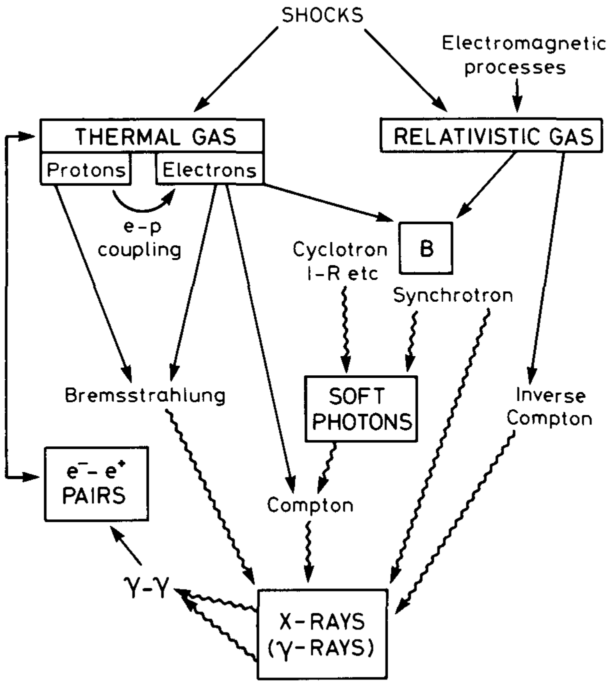

Figure 1. X-radiation processes.

may be showing that most of the radiating electrons are quasi-thermal. Pair production in hot plasmas acts as an efficient thermostat to limit temperatures to below a few 10^9K, (Lightman, 1982; Svensson, 1982), thereby naturally giving a break in the spectrum around an MeV. That energy does not, however, have any particular significance if the underlying electron population is highly relativistic. The most likely explanation for the break is then photon-photon collisions within the source, which means that most of the energy goes into mildly relativistic pairs (since the flat spectrum implies $\nu F\nu$ increases with ν). These, then, would do most of the radiating (Comptonized bremsstrahlung, cyclotron etc) and the situation would be similar to that in which the pairs were thermal anyway. The main conclusion of this is that the electrons (and positrons) that produce the observed radiatron predominantly have an energy of $\sim$ 1 MeV.

Unfortunately, there is then no easy way of explaining the small dispersion in spectral index observed from active galaxies. Lightman (1981) and Rothschild et al. (1982) have noted the similarity of that spectral index to the radio continuum in a wide variety of situations. Shocks can probably give the correct spectral index for highly relativistic electrons. Steady-state Comptonized bremsstrahlung (Guilbert, 1982) and cyclotron emission (Takahara & Tsuruta, 1982) appear to give the required shape only for a restrictive range of optical depth. A serious problem in this case arises even at modest optical depths (e.g. $\lesssim 3$ if $kT \sim m_ec^2$) due to the formation of a Wien peak at the gas temperature. Such peaks have never been seen in active galaxy spectra.

This problem is partially alleviated if Compton-cooled plasmas, in which the gas cools in response to the energy transfer to photons, are considered (Guilbert, Fabian & Ross, 1982). Time-averaged spectra show no Wien peaks and even the instantaneous spectra in rapidly varying situations are power laws because it takes considerably longer to populate a Wien peak than to scatter photons up to around kT_e. Detailed calculations including Comptonization, bremsstrahlung, pair-production (and possibly even cyclotron which may dominate the infrared emission) are required before any firm statements can be made about the spectral index to be expected from compact sources of mildly-relativistic gas.

5. X-IRRADIATED GAS

The X-rays from Seyfert galaxies can efficiently heat a tenuous surrounding gas. The hard spectrum means that the highest temperature attainable - the Compton temperature - is ∿ 20 keV, and also that a two-phase medium is possible (McCray, 1979; Krolik, McKee & Tarter, 1981). Dense, cool and partially recombined gas (e.g. 10^{10} particles cm^{-3} at 10^4K) can co-exist in pressure equilibrium with tenuous, hot, highly ionized gas (e.g. 10^6 cm^{-3} at 10^8K). Atomic processes keep the cool gas cool, whereas the hot gas is dominated by the Compton interactions. Such a two-phase medium is the broad-line region in the Seyfert nuclei, with the optical emission originating in the cool clouds.

We have recently pointed out that the steep soft X-ray spectra characteristic of BL Lac objects prevents the formation of a broad-line region (Guilbert, Fabian & McCray, 1982). The Compton temperature is much lower than in the case of Seyferts and no two-phase medium is possible. Indeed if the central source in a Seyfert galaxy were to emit a BL Lac-type spectrum, the broadline clouds would disperse and both the previously cool and hot gases would merge into a highly ionized region at a temperature of less than 10^6K. The optical emission lines from such a gas would be undetectable. Interestingly, the Galactic binary X-ray source Cygnus X-1 changes between two states, the spectra of which are similar to those of Seyferts (low state; flat) and of BL Lac objects (high state; steep). (The turnover however occurs closer to 200 keV than 1 MeV.) Perhaps Seyferts occasionally turn into BL Lac objects and vice versa. The timescale for obliteration of the broad-line region is typically 100 years. The two states of Cyg X-1 can be explained by means of an internal feedback mechanism involving Comptonization (Guilbert & Fabian, 1982). The optically lineless spectra of BL Lac objects thus do not necessarily require relativistic beams directed towards us (Blandford & Rees, 1978), although these do help the synchro-self-Compton interpretation of the X-ray spectra (Urry &

Mushotzky, 1982). The pressure in a highly ionized, million degree BL Lac irradiated gas is $\gtrsim$ 100 times lower at the same density than that in a Seyfert nucleus. Consequently it is possible that any beams might be less collimated in BL Lacs and that the radio structures might be markedly different. The presence of broad-lines in quasars suggests that they have relatively hard X-ray spectra.

The extent of any two-phase medium in a source with a hard spectrum is increased (to include smaller radii) if the soft X-rays are absent (Guilbert, Fabian & McCray, 1982). This could arise as a result of photoelectric absorption in the shadows of moving cool clouds. There is thus some feedback such that if some clouds are formed at small radii, they promote the formation of further clouds. The general low-energy absorption observed in sources with X-ray luminosities $\lesssim 10^{43}$ erg s^{-1} may be due to this mechanism. This luminosity is important if the hot phase is being accreted, since it corresponds to the level at which the heating timescale equals the free-fall timescale (for a $10^8 M_\odot$ central mass). The cool clouds may, of course, be moving differently under the influence of radiation pressure.

6. SUMMARY

The X-rays from active galactic nuclei appear to dominate the emission from the central source and control the behaviour of the surrounding matter. Further observations of the spectrum and variability in the X- and soft γ-ray energy bands together with theoretical studies of mildly relativistic plasmas should continue to be very worthwhile.

ACKNOWLEDGEMENTS

I thank the Royal Society for financial support.

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